The composition of the interstellar medium in the Galaxy as seen through X-rays

Ciro Pinto
**Cover image:** The central regions of the Milky Way as seen by NASA’s three Great Observatories. Blue and violet represents the X-ray observations of Chandra. X-rays are emitted by gas heated to millions of degrees by stellar explosions and by outflows from the supermassive black hole in the Galaxy center. Yellow represents the near-infrared observations of Hubble. They outline the energetic regions where stars are being born as well as reveal hundreds of thousands of stars. Red represents the infrared observations of Spitzer. The radiation and winds from stars create glowing dust clouds that exhibit complex structures from compact, spherical globules to long, stringy filaments. (Image courtesy: X-ray: NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D.Wang et al.; IR: NASA/JPL-Caltech/SSC/S.Stolovy. This image has been edited by adding an artistic view of the Andromeda constellation and of an aquatic electric guitar, which underline my passions for arts and music.

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Proefschrift

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Chapter 1

Introduction

The term “Milky Way” usually refers to the hundreds billion stars of our Galaxy, which emit most of its visible light. This name derives from its appearance as a weak “milky” band which arches across the night sky. It is made of individual stars that cannot be distinguished by the naked eye as it is also the case for the other galaxies. However, the environment around the stars is not empty, it hosts a very tenuous medium which is called “interstellar medium” (ISM). The ISM contains matter in the form of gas and dust as well as cosmic rays (relativistic charged particles) and magnetic fields. Thermonuclear fusion in stellar interiors enrich the ISM with heavy elements like oxygen and iron in a gradual and continuous way through stellar winds or instantaneously through supernova explosions. Eventually dust and molecules are produced. These processes also alter the physical structure of the ISM as their different energy releases heat the matter and give rise to a multiphase structure. Part of the interstellar matter is then used to give birth to new stars whose chemical structure and metallicity differ from the previous generations (for an image of a big star forming region, see Fig.1.1). Cosmic rays and magnetic fields affect the dynamics of the interstellar matter through the electromagnetic force and provide it a support against the gravitational force. The matter confines the former ones to the Galaxy, accelerates cosmic rays and amplifies the magnetic fields. The ISM is therefore an active component of the Galaxy which exchanges matter and energy with stars and affects many of their properties, and highly influences the Galactic evolution.

1.1 The multiphase structure of the ISM

In the Milky Way - and in general in spiral galaxies - gas and dust are mostly found within a thin disk with a thickness of a few hundred pc (see Finkbeiner 2003 and
Kalberla et al. 2005). This gaseous disk is defined as thin because its thickness is much smaller (~ 6%) than the distance of the Sun from the Galactic center, which is ~ 8 kpc (for a recent estimate, see e.g. Malkin 2012). The total mass of the Galaxy is about $10^{11} M_\odot$, mostly provided by stars and dark matter. The ISM contributes less than 10%, but star formation takes place only in the region hosting the ISM. About 60% of the interstellar hydrogen is contained in H atoms, while the remainder is equally shared between H$_2$ molecules and H II ionized gas. However, the interstellar gas can extend well beyond the thin disk but its structure varies with the latitude. The interstellar (IS) matter covers large ranges of temperature and density, which is due to the dynamical processes of stellar evolution and the effects of several heating sources such as cosmic rays. Interestingly, most of the IS matter is found near some characteristic phases, each of them with a certain temperature regime. There are several ways to interpret the ISM phases and here for simplicity we identify three main phases (see Table 1.1). Each of these phases has a different scale height with respect to the Galactic plane and thus, at a certain location within the Galaxy, the ISM structure depends on the ratio between these phases. In Fig. 1.2 we show the distribution of the molecular, neutral, and ionized gas components as function of the Galactocentric radius and the height from the Galactic plane. We can simplify the ISM structure as follows.

- **Cold phase:** it is a complex phase containing dust, molecules, and gas at low temperatures below 100 K. This cold matter is commonly ionized by starlight and cosmic rays and then heated by photoelectrons irradiated from dust. These components cool down by fine structure line emission (see e.g. Draine 2011 and references therein). The molecular gas spans a huge range of density from $n_H \sim 100 \text{ cm}^{-3}$ typical of the diffuse medium to $10^3-6 \text{ cm}^{-3}$ in the dense molecular clouds. In these dense clouds dust is also present and characterized by carbonaceous and/or silicate compounds covered with molecular ice like H$_2$O. These clouds are important because star formation takes place therein. Despite its important role, the cold phase occupies just 1% of the ISM volume. This phase is commonly studied at long wavelengths. Molecular and atomic gas is well studied through the H1 21 cm emission and absorption lines or the CO 2.6 mm emission line in the radio band. In some cases optical and UV absorption lines also provide an important workbench. Dust is mostly probed through IR/FIR

<table>
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<th>Phase</th>
<th>Component</th>
<th>T (K)</th>
<th>$n_H$ (cm$^{-3}$)</th>
<th>Indicators</th>
<th>Heating/ionizing sources</th>
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<tr>
<td>cold</td>
<td>molecules</td>
<td>10 − 20</td>
<td>$10^2 - 10^6$</td>
<td>H$_2$, CO, ...</td>
<td>Dust, starlight, cosmic rays</td>
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<tr>
<td></td>
<td>neutral gas</td>
<td>50 − 100</td>
<td>20 − 50</td>
<td>HI, OI, ...</td>
<td>Dust, starlight, cosmic rays</td>
</tr>
<tr>
<td>warm</td>
<td>neutral gas</td>
<td>(5 − 10) × $10^3$</td>
<td>0.2 − 0.6</td>
<td>HI, OI, ...</td>
<td>Dust, starlight, cosmic rays</td>
</tr>
<tr>
<td></td>
<td>ionized gas</td>
<td>~ 8 000</td>
<td>0.2 − $10^4$</td>
<td>H II, O II−III, ...</td>
<td>UV photons from hot stars</td>
</tr>
<tr>
<td>hot</td>
<td>ionized gas</td>
<td>~ $10^6$</td>
<td>4 − $6 \times 10^{-3}$</td>
<td>O VI–VIII, ...</td>
<td>Shockwaves from SNe</td>
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</table>
1.1 The multiphase structure of the ISM

The largest, most violent star forming region known in the whole Local Group of galaxies lies in our neighboring galaxy the Large Magellanic Cloud (LMC). Were the Tarantula Nebula at the distance of the Orion Nebula, a local star forming region, it would take up half the sky. (Image Credit: NASA, ESA, ESO, D. Lennon (ESA/STScI) et al., and the Hubble Heritage Team (STScI/AURA)).

Figure 1.1: The largest, most violent star forming region known in the whole Local Group of galaxies lies in our neighboring galaxy the Large Magellanic Cloud (LMC). Were the Tarantula Nebula at the distance of the Orion Nebula, a local star forming region, it would take up half the sky. (Image Credit: NASA, ESA, ESO, D. Lennon (ESA/STScI) et al., and the Hubble Heritage Team (STScI/AURA)).

- **Warm phase:** it consists of a blend of neutral and ionized gas with temperatures of about $10^3$–$10^4$ K. The warm neutral gas has a density much lower than the cold gas (see Table 1.1), but it is thought to fill up to 40% of the volume of the Galactic disk. It has a typical temperature of about 5000 K and gives rise to optical line emission in addition to the spectral features produced by the cold gas too. The warm ionized gas ($T \sim 8000$ K) is photoionized by UV emission from hot, mostly O, stars. This gas also shows a large range of densities whose peaks of $10^4$ cm$^{-3}$ are found in H II regions, like the Orion Nebula, surrounding young hot stars or in planetary nebulae formed around stars with a large mass loss. The photoionization regions extend into the interstellar space, reach densities of about 0.2 cm$^{-3}$, and contain most of the ionized hydrogen. The photoionized gas is thus found to be either expanding or in pressure equilibrium. It cools down through free-free,
optical, and fine-structure line emission. Therefore it is well probed with studies of optical emission lines and thermal radio continuum. It is thought to have a volume filling factor of about 10% and a scale height of 500 pc.

- **Hot phase**: it is characterized by highly ionized gas with temperatures higher than $10^{5.5}$ K. This gas is heated by shockwaves originating in supernova explosions. It is collisionally ionized and shows high ionization states like O VI and higher. This component is also called coronal gas because its physical state is very similar to that of stellar coronae. Its density is very low, but it is thought to fill about 50% of the Galactic disk. The hot gas cools down through adiabatic expansion and X-ray emission. Therefore, it is well studied through its UV absorption and X-ray absorption and emission as well as with radio synchrotron emission.

### 1.2 Metal enrichment and composition of the ISM

The Big Bang gave origin to most of the hydrogen and helium atoms. Heavier elements like those from carbon to uranium$^1$ have been formed after during the course of stellar evolution either through nucleosynthesis in stellar cores or in supernova explosions. Although these other elements contain just 1% of the total baryonic mass, they are crucial to understand the chemical composition and physical state of the gas. In Fig. 1.3 we show the elemental abundances for the Solar system, which is also called cosmic composition, as recently estimated by Lodders & Palme (2009). The elemental composition of the ISM is similar to the cosmic composition.

$^1$In astronomy all the elements with $Z > 2$ are often called metals.
Absorption and emission lines produced by different ionization states of metals provide the temperatures, velocities, and other important physical parameters. Moreover the ratios between the column densities of interstellar metals and that of hydrogen, also known as absolute abundances, directly yields the contribution of the stellar evolution to the metal enrichment of the ISM. The heavy elements such as oxygen (the most abundant one) and iron are produced in high-mass stars. Nitrogen atoms, molecules and dust compounds are mainly formed in AGB stars and then grow in the diffuse ISM (see e.g. Mattsson & Andersen 2012). The asymptotic giant branch (AGB) is the region of the Hertzsprung-Russell diagram characterized by evolved low to medium-mass (0.6-10 solar masses) stars. Elements heavier than Si, such as Ca, Fe, and Ni, are mostly provided by supernova type Ia (SN Ia). A SN Ia is a sub-category of supernovae that results from the violent explosion of a white dwarf star. A white dwarf is the remnant of a star that has completed its normal life cycle and has ceased nuclear fusion. If a white dwarf gradually accretes mass from a binary companion, the general hypothesis is that its core will reach the ignition temperature for carbon fusion as it approaches the limit. Within a few seconds after initiation of nuclear fusion, a substantial fraction of the matter in the white dwarf undergoes a runaway reaction, releasing enough energy to unbind the star in a supernova explosion. A Type II supernova (SN II, also known as
core-collapse supernova) results from the rapid collapse and violent explosion of a massive star. A star must have at least 8 times, and no more than 40 – 50 times the mass of the Sun for this type of explosion. It is distinguished from other types of supernovae by the presence of hydrogen in its spectrum. SN II provide most of the interstellar oxygen and neon. Therefore, it is clear that heavy elements directly witness the history of the past stellar evolution.

Some spiral galaxies show an ISM composition similar to that of our Galaxy, while other galaxies have a different metallicity. In Fig. 1.4 we show an interesting plot by Konami et al. (2009) for the abundances in the hot phase of the ISM of some nearby galaxies. Through the study of the X-ray emission of the hot gas, they determined the abundance pattern in the nearby spiral galaxy NGC 4258, which was found to be consistent with the cosmic abundances of Lodders (2003), while in the case of the starburst galaxy M 82 the abundances were closer to the supernovae type II pattern. As expected, the ordinary spiral NGC 4258 had an enrichment process similar to our Galaxy, while it was clearly different in the starburst galaxy.

Stellar winds and supernovae expel part of the interstellar gas out of the Galactic disk, but gravity generally forces the gas to fall back through the process known as “Galactic fountain” (Shapiro & Field 1976). However, the ISM metallicity does not grow monotonically in the Galaxy. Gas accreted from smaller galaxies, like the Magellanic Clouds, and the intergalactic medium increases the reservoir of low metallicity gas. This process is revealed through observations of high-velocity clouds (HVCs), i.e. interstellar clouds with \( v \lesssim -90 \text{ km s}^{-1} \). These clouds do not match the Galactic rotation curve and are thought to belong to extragalactic matter (usually with sub-Solar metallicities) infalling into the gravitational field of the Galaxy (for a review on HVCs, see Wakker & van Woerden 1997).

In the ISM the dust-to-gas mass ratio is about \( 0.005–0.01 \) (see e.g. Kim & Martin 1996 and Frisch & Slavin 2003). However, hydrogen cannot provide a main contribution to grain mass and species like neon and helium are inert. Therefore it is natural to think that most of the dust mass is provided by the other highly abundant elements which can condensate into dust grains: carbon, oxygen, magnesium, silicon, and iron. Indeed, several studies confirmed that about 60% of C and more than 90% of Mg, Si, and Fe are missing (or depleted) from the gaseous phase and are presumably locked up into dust grains (for a review about depletion in the ISM, see Jenkins 2009). Oxygen also shows significant depletion factors up to 40%, but it is not well understood what compounds can account for this. If we sum all the possible contributions from silicates, carbonaceous oxides and ices, there is still about 25% of the total oxygen missing (with respect to the amount predicted by the Solar oxygen abundance, see Whittet 2010).

### 1.3 First observational evidence of the ISM

The interstellar matter, as a mixture of dust, gas, and molecules, manifests itself primarily through obscuration, reddening, polarization, and scattering of starlight and the formation of absorption lines in stellar spectra. On the other hand, it also produces various emission components like broadband continuum (thermal and microwave emis-
1.3 First observational evidence of the ISM

Figure 1.4: Number ratios of O, Ne, Mg, Si, and S to Fe for the two and three-temperature models of the ISM in NGC 4258 together with other results on NGC 4631 and M 82 (see Konami et al. 2009 and references therein). Solid and dashed lines indicate the number ratios of metals to Fe by Lodders (2003) and Anders & Grevesse (1989), respectively. Dot-dashed and dotted lines represent the number ratios of metals to Fe for the SN II and SN Ia products (Iwamoto et al. 1999 and Nomoto et al. 2006).

The discovery of the interstellar medium is a rather recent event in the history of the Astronomy. The first hypothesis posing the existence of an absorbing medium lying between the stars of our Galaxy came out towards the end of the nineteenth century when astronomers thought that this medium was responsible for the dark zones in the long-exposure pictures of the Milky Way taken by Edward Barnard (see e.g. McNally 1929 and references therein). The ISM is filled with dust which absorbs or scatters the starlight through the processes known as interstellar obscuration and extinction. These phenomena would also explain the disagreement between the Galactic structure as determined by Shapley and Kapteyn. Shapley used the Galactic distribution of globular clusters and argued that its center should coincide with the center of the Galaxy. He also estimated that the Sun is 15 kpc away from the Galactic…
center, which is a factor of 2 higher than what we currently know (see Sect. 1.1). Herschel and Kapteyn used the distribution of stars across the sky assuming that they have the same intrinsic brightness and that the interstellar space was transparent to starlight (both assumptions were wrong). Therefore, they estimated that the Galaxy was about 1 kpc large and thus much smaller than the current estimates ($r_{\text{disk}} \sim 25 - 30$ kpc), and that the Sun was located near the Galactic center. The presence of obscuring interstellar matter gave Herschel and Kapteyn the false impression that the spatial density decreases isotropically in any direction away from us and brought them to misplace the Sun near the center of the Galaxy. Shapley did not encounter the same problem with globular clusters, because they are intrinsically much brighter and easier to recognize than individual stars and because most of them lie outside the thin layer of obscuring material.

The first direct evidence of the ISM was the discovery of stable Ca II absorption lines in the spectrum of the spectroscopic binary $\delta$ Orionis (Hartmann 1904). Lines intrinsic to the binary systems are generally variable and Doppler-shifted. Trümpler (1930) first discovered that the reddening of stars of a certain spectral type (i.e. the absorption of the blue / short wavelengths) increases with the distance, which brought the idea that the interstellar space contains dust that produces absorption and extinction. Strong evidence of the interstellar medium and spatial distribution of interstellar H I was obtained in the second half of the twentieth century through observations with radio telescopes (see e.g. Binney & Merrifield 1998 chapter 10 and references therein). These observations showed that the interstellar H I follows a spiral structure similar to that observed in external galaxies. The Sun was indeed far away from the center of the spiral arms but at a two times smaller distance than that predicted by Shapley.

### 1.4 X-ray spectroscopy of the ISM

In X-rays the ISM produces several emission or absorption phenomena, nevertheless X-ray astrophysics of the ISM is a very young science, whose development started with the discovery of the ISM hot phase. Spitzer (1956) predicted the existence of a hot coronal phase in the ISM, which was required to provide sufficient pressure to confine observed high-altitude clouds. However, only in the seventies the first evidence of the hot gas was revealed in the UV energy domain with the Copernicus satellite (York 1974) and in X-rays with rocket missions (Williamson et al. 1974). The analysis of the soft X-ray background at 0.25 keV indicated that most of the emitting gas was located within the Local Bubble with temperatures of about $10^6$ K (see Cox & Reynolds 1987 and McCammon & Sanders 1990a). Important improvements in the study of the emission of the hot gas were provided by the launch of the ROSAT satellite (see Fig. 1.5), which brought discovery of emission from regions outside the Local Bubble and even from extragalactic space (Snowden et al. 1998). The launch of new X-ray missions like Chandra, XMM-Newton, and Suzaku improved the study of the ISM. However, X-ray emission lines are suitable only for determining the physics and chemistry of the hot phase of the ISM either in the Milky Way (see e.g. Hagihara et al. 2011) or in external galaxies such as M31 (Liu et al. 2010) and NGC 4258 (Konami et al. 2009).
In the X-ray spectra of background sources the ISM gives rise to absorption features at a wide range of energies and ionization states. X-ray absorption spectroscopy is an ideal tool to measure the metal abundances of the ISM, in most forms and phases. The X-ray energy band contains almost all the K-shell and L-shell transitions of different charge states of the abundant elements from carbon to iron. X-ray spectroscopy also probes larger column densities than can be measured in the optical and UV band, because it is less affected by extinction, and is thus very useful for measuring the properties of the ISM through much of the Galactic disk. However, the spectral resolution and sensitivity of the currently available X-ray telescopes is still limited such that only the most abundant elements (like oxygen, neon, and iron) can produce significant absorption features in the spectra of bright background sources like AGNs and X-ray binaries.

Schattenburg & Canizares (1986) observed the Crab nebula with the Einstein Observatory in order to understand the emission from the pulsar and the nebula, and measured – for the first time – ISM absorption edges in the X-ray band and found features consistent with the O I 1 s – 2p line and traces of O II. However, only after the launch of the XMM-Newton and Chandra satellites a new era for the ISM study opened up. The grating spectrometers onboard these satellites, RGS (Reflection Grating Spectrometer) and LETGS/HETGS (Low-energy / High-energy Transmission Grating Spectrometer) respectively, provide a spectral resolution that is high enough to resolve the main absorption edges and lines. For instance, Kaastra et al. (2009) observed the Crab nebula with the XMM-Newton/RGS and measured column densities for neutral species like H, N, O, Ne, Mg, and Fe with an accuracy much higher than before and uncertainties of a few percents.
Some years before, Paerels et al. (2001) observed the low-mass X-ray binary (LMXB) 4U 0614+091 with the aim of probing emission lines intrinsic to the source, which were discovered a few years before. They did not find any of those lines, but detect K-shell absorption by interstellar O and Ne, and L-shell absorption by Fe. From this moment it became clear that X-ray spectroscopy has indeed the power to probe the ISM. A first dedicated study on the ISM was carried by Juett et al. (2004). They observed a small sample of X-ray binaries with the HETGS onboard Chandra and measured column densities of neutral, singly and doubly ionized oxygen. They constrained some ionization ratios for the interstellar gas: $\frac{O^{\text{II}}}{O^{\text{I}}} \sim 0.1$ and $\frac{O^{\text{III}}}{O^{\text{I}}} \lesssim 0.1$. They also estimated the velocity dispersion of the neutral lines to be $\lesssim 200 \text{ km s}^{-1}$, which suggests that the absorption lines originate in the ISM rather than in a circumstellar environment local to the binaries. A couple of years later, Juett et al. (2006) extended the analysis to the Ne and Fe edges and measured interesting abundance ratios: $\frac{O}{Ne} = 5.4 \pm 1.6$ and $\frac{Fe}{Ne} = 0.20 \pm 0.03$. The first was consistent with the standard ISM abundances (Wilms et al. 2000), while the latter was significantly lower. They attributed this difference to iron depletion into dust grains in the interstellar medium. They also measured large degrees of ionization: $\frac{Ne^{\text{II}}}{Ne^{\text{I}}} \sim 0.3$ and $\frac{Ne^{\text{III}}}{Ne^{\text{I}}} \sim 0.07$. This was just the prelude to a big series of discoveries.

Yao & Wang (2005) systematically studied the hot gas towards a sample of 12 sources, mostly LMXBs, and obtained a typical temperature of about $2 \times 10^6 \text{ K}$ and a scale-height of about 1 kpc. Yao & Wang (2006) first constrained the multiphase structure of the ISM through high-resolution X-ray spectroscopy of the cold, warm, and hot phases. They measured column densities of oxygen on a broad range of ionization states as well as oxygen abundances (by comparing their oxygen column densities with the hydrogen measurements at 21 cm). The cold and warm gas respectively provided $\frac{O}{H} = 0.2 - 0.6$ and $1.1 - 3.5$ (in units of Solar abundances, see Anders & Grevesse 1989), which was interpreted as a result of molecule/dust grain destruction and recent metal enrichment in the warm ionized and hot phases. Recently, Yao et al. (2009a) found high-ionization absorption lines of ions such as O $^{\text{VI}}$ to O $^{\text{VIII}}$ and Ne $^{\text{VIII}}$ to Ne $^{\text{X}}$ in the HETGS spectrum of the low-mass X-ray binary Cyg X-2, and argued that the bulk of the O $^{\text{VI}}$ should originate from the conductive interface between the cool and the hot gas in accordance with Richter (2006).

Other work has revealed a complex structure around the oxygen K-shell absorption edge (de Vries et al. 2003). Lee & Ravel (2005) proposed to use the iron absorption edges for determining quantity and composition of interstellar dust. This was successfully applied to Chandra/HETGS observations of the X-ray binary Cygnus X-1 by Lee et al. (2009), who found evidence for hematite and iron silicates. More work on interstellar dust followed. Costantini et al. (2005) argued that the feature near the O $^{\text{I}}$ K-edge of the scattering halo of Cyg X-2 can be attributed to dust towards the source, with a major contribution from silicates such as olivine and pyroxene. In their paper on Sco X-1, observed with XMM-Newton, de Vries & Costantini (2009) found clear indications of extended X-ray absorption fine structures (EXAFS) maybe due to dust near the absorption edge of oxygen. Costantini et al. (2012) combined Chandra and XMM-Newton spectra of the bright LMXB 4U 1820-303 and found the dust to provide about 20% of oxygen and 90% of iron. They also suggested a major contribution of Mg-rich
silicates, with metallic iron inclusion, and a composition similar to the well studied dust constituent (GEMS), sometimes proposed as a silicate constituent in our Galaxy.

The current X-ray satellites will be operating for most of this decade and a new X-ray mission (ASTRO–H, Takahashi et al. 2010) will be launched in two years from now. The soft X-ray Calorimeter Spectrometer (SXS) onboard this satellite will provide for the first time a high spectral resolution in the broad 0.3–12 keV energy band combined with high sensitivity and the possibility of a simultaneous analysis of the Fe K and L edges as well as high quality Mg and Si absorption spectra. Lee et al. (2009) showed that it is indeed possible to differentiate dust constituents with the SXS.

1.5 Thesis aims and structure

It is clear that high-resolution X-ray spectroscopy provides an important workbench for the study of the ISM and it is worth to say that we are in the golden age of the ISM X-ray spectroscopy. The current and future X-ray satellites provide accurate estimates of interstellar column densities, ionization states, and depletion factors, which are useful to determine the chemical and physical state of all the phases of the ISM. However, a systematic study on this field is yet to be done and there are several open questions on the ISM. What is the exact molecular structure of the cold interstellar phase? What are the depletion factors? Is any phase in a certain equilibrium state and which one? What are the total elemental abundances? How do all these parameters relate to the specific Galactic environment? How do the abundances vary in the Galaxy and how are they correlated with the metal enrichment provided by AGB stars, supernovae and other sources?

This thesis aims to find and provide a solution to some of these problems. In particular we focus on the study of the ISM through high-resolution X-ray spectroscopy of bright background sources. The analysis of its absorption lines provides us with accurate measurements of column densities and abundances for several elemental species. This allows us to determine the multiphase structure and the chemical composition of the ISM. We also measure the metallicity gradient of the ISM in the Galaxy which depends on the stellar elemental yields, and it is thus linked to the evolution of the Galaxy.

- In Chapter 2 we show a simple approach to determine the multiphase structure of the ISM through the observation of its absorption lines and edges in the high-quality X-ray spectrum of the LMXB GS 1826–238. We provide an unprecedentedly detailed treatment of the absorption features caused by the dust and both the neutral and ionized gas of the ISM. We constrain the column density ratios within the different phases of the ISM and measure the abundances of elements such as O, Ne, Fe, and Mg. There are significant deviations from the proto-Solar abundances, which are consistent with the Galactic metallicity gradient: the ISM appears to be metal-rich in the inner regions. Up to about 10% of the gas is ionized. Signatures of dust and molecules are also clearly detected: they account for most iron and between 10 and 40% of oxygen.
• The metal enrichment in the ISM is a product of stellar evolution, but each type of star releases a certain amount of metals in the surrounding space depending on the detailed nucleosynthesis. Novae are a subclass of cataclysmic variables consisting of a white dwarf (WD) that accretes gas (mostly hydrogen) from a companion star. When the accretion of matter surpasses a certain limit then hydrogen in the WD outer layer starts to burn into helium and pulls out matter from the WD into the surrounding medium, which is enriched by metals and dust. In Chapter 3 we show that the deep absorption lines of the X-ray spectrum of nova V2491 Cyg are well described by a phenomenological model consisting of three highly ionized expanding shells. Rest-frame absorption lines are produced by cold circumstellar and interstellar matter that includes dust. The abundances of the shells indicate that they were ejected from an O-Ne white dwarf. High abundances of O and N in the cold absorbing gas shows that the surrounding medium is significantly enriched of metals by the nova ejecta.

• The ISM structure varies with the Galactic altitude. Near the Galactic plane most of the matter is stored in cold gas and dust, while at higher altitudes the ionized gas has a predominant role. AGNs are optimal background sources for the analysis of the ISM in the disk and halo of the Galaxy as several of them are bright and have column densities high enough to show strong interstellar absorption features. In Chapter 4 we use high-quality X-ray and UV spectra of AGN Mrk 509, located at intermediate-high Galactic latitudes obtained with XMM-Newton, HST and FUSE. We use advanced absorption models consisting of photo- and collisional-ionization in order to constrain the column density ratios of the different phases of the interstellar medium (ISM) and measure the abundances of C, N, O, Ne, Mg, Al, Si, S, and Fe. The high-resolution UV spectra allow to differentiate between up to seven velocity components, which belong to different kinds of interstellar clouds. We determine their origin and location within the Galactic environment.

• In Chapter 5 we show a simple method to probe the ISM dust composition, total abundances, and abundance gradients through the study of interstellar absorption features in the high-quality spectra of nine LMXBs taken with XMM-Newton. We measure the column densities of O, Ne, Mg, and Fe with an empirical model and estimate the Galactic abundance gradients. We find that solid oxygen is mostly provided by ices and silicates. 15–20% and 70–90% of the total amount of O I and Fe I is found in dust, respectively. The amount and composition of dust seems to be consistent along all lines-of-sight (LOS). On a large scale the ISM appears to be chemically homogeneous showing similar gas ionization ratios and dust mixtures. The agreement between the abundances of the ISM and the stellar objects suggests that the local Galaxy is also chemically homogeneous.
High-resolution X-ray spectroscopy of the Interstellar Medium

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Abstract

The interstellar medium (ISM) has a multiphase structure characterized by gas, dust, and molecules. The gas can be found in different charge states: neutral, weakly ionized (warm) and highly ionized (hot). It is possible to probe the multiphase ISM through the observation of its absorption lines and edges in the X-ray spectra of background sources. We present a high-quality RGS spectrum of the low-mass X-ray binary GS 1826−238 with an unprecedentedly detailed treatment of the absorption features caused by the dust and both the neutral and ionized gas of the ISM. We constrain the column density ratios within the different phases of the ISM and measure the abundances of elements such as O, Ne, Fe, and Mg. We found significant deviations from the protosolar abundances: oxygen is over-abundant by a factor $1.23 \pm 0.05$, neon by $1.75 \pm 0.11$, iron by $1.37 \pm 0.17$, and magnesium by $2.45 \pm 0.35$. The abundances are
consistent with the measured metallicity gradient in our Galaxy: the ISM appears to be metal-rich in the inner regions. The spectrum also shows the presence of warm and hot ionized gas. The gas column has a total ionization degree of less than 10%. We also show that dust plays an important role as expected from the position of GS 1826–238: most iron appears to be bound in dust grains, while 10–40% of oxygen consist of a mixture of dust and molecules.

2.1 Introduction

The interstellar medium of our Galaxy (ISM) is a mixture of dust and gas in the form of atoms, molecules, ions, and electrons. It manifests itself primarily through obscuration, reddening and polarization of starlight and the formation of absorption lines in stellar spectra, and secondly through various emission mechanisms (broadband continuum and line emission). The gas is found in both neutral and ionized phases (for a review, see Ferrière 2001). The neutral phase is a blend of cold molecular gas ($T \sim 20 – 50$ K), found in the so-called dark clouds, and cold atomic gas ($T \sim 100$ K) inherent in the diffuse clouds, while the warm atomic gas has temperatures of up to $10^4$ K. The atomic gas is well traced by H I and mainly concentrated in the Galactic plane with clouds up to few hundreds pc above it. The warm ionized gas is a weakly ionized gas, with a temperature of $\sim 10^4$ K. It is mainly traced by Hα-line emission and pulsar dispersion measures; it can reach a vertical height of 1 kpc. The hot ionized gas is characterized by temperatures of about $10^6$ K. It is heated by supernovae and stellar winds from massive stars; it gives rise to high-ionization absorption lines and the soft X-ray background emission. The study of the ISM is very interesting because of its connection with the evolution of the entire Galaxy: the stellar evolution enriches the interstellar medium with heavy elements, while the ISM acts as a source of matter for the star-forming regions.

High-resolution X-ray spectroscopy has become a powerful diagnostic tool for constraining the chemical and physical properties of the ISM. Through the study of the X-ray absorption lines in the spectra of background sources it is possible to probe the various phases of the ISM of the Galaxy. First of all, the K-shell transitions of low-Z elements, such as oxygen and neon, and the L-shell transitions of iron fall inside the soft X-ray energy band. Secondly, the different charge states for each element allow us to constrain the multiphase ISM, e.g. its ionization state and temperature distribution.

Schattenburg & Canizares (1986) first measured ISM absorption edges in the X-ray band with the Einstein Observatory and found features consistent with the O I $1s – 2p$ line and traces of O II. After the launch of the XMM-Newton and Chandra satellites a new era for the ISM study opened up. The grating spectrometers onboard these satellites, RGS and LETGS/HETGS respectively, provide a spectral resolution that is high enough to resolve the main absorption edges and lines. Recently, Yao et al. (2009a) found high-ionization absorption lines of ions such as O VI to O VIII and Ne VIII to Ne X in the HETGS spectrum of the low-mass X-ray binary Cyg X-2, and argued that the bulk of the O VI should originate from the conductive interface between the cool and the hot gas. Other work has revealed a complex structure around the oxygen K-shell
2.2 Observations and data reduction

Table 2.1: Observations used in this paper. We report the total exposure length together with the net exposure time remaining after screening of the background and removal of bursts.

<table>
<thead>
<tr>
<th>ID</th>
<th>Date</th>
<th>Length (ks)</th>
<th>RGS (ks)</th>
<th>PN (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0150390101</td>
<td>2003 April 6</td>
<td>108</td>
<td>67.8</td>
<td>63.8</td>
</tr>
<tr>
<td>0150390301</td>
<td>2003 April 8</td>
<td>92</td>
<td>77.8</td>
<td>67.8</td>
</tr>
</tbody>
</table>

absorption edge (Paerels et al. 2001; de Vries et al. 2003; Juett et al. 2004). Costantini et al. (2005) argued that the feature of the scattering halo of Cyg X-2 near the O I K-edge can be attributed to dust towards the source, with a major contribution from silicates such as olivine and pyroxene. In their paper on Sco X-1, observed with XMM-Newton, de Vries & Costantini (2009) found clear indications of extended X-ray absorption fine structures (EXAFS) near the absorption edge of oxygen.

In this work we report the detection of absorption lines and edges in the high-quality spectrum of the low-mass X-ray binary (LMXB) GS 1826–238 obtained with the XMM-Newton Reflection Grating Spectrometer (RGS, den Herder et al. 2001). In order to constrain the continuum parameters we also used the EPIC-pn (Struder et al. 2001) dataset of this source. Thompson et al. (2008), using the XMM-Newton and RXTE observations of April 2003, derived a high unabsorbed bolometric flux $F \sim 3.5 \times 10^{-12}$ W m$^{-2}$. The source is well suited for the analysis of the ISM also because of its column density $N_H \sim 4 \times 10^{25}$ m$^{-2}$ (see Table 2.3), which is sufficiently high to produce prominent O and Fe edges. We assume the distance of the source to be $6.1 \pm 0.2$ kpc (Heger et al. 2007).

We analyze the absorption in the spectrum as follows. We first remove the bursts, because they add a strongly variable component to the spectrum. Then we determine the source continuum by simultaneously fitting EPIC and RGS data. In a second instance we use only the high-resolution RGS spectra to constrain the absorption contributions. We search for statistically significant features by adding several absorbers in sequence: cold gas, warm gas, hot gas, dust, and molecules. All of these appear to be important.

2.2 Observations and data reduction

The source GS 1826–238 (Galactic coordinates $l = 9^\circ.27$, $b = -6^\circ.09$) has been observed twice with XMM-Newton for a total length of 200 ks (see Table 5.1 for details). The data are reduced with the XMM-Newton Science Analysis System (SAS) version 9.0.1.

GS 1826–238 is a bursting LMXB with a regular time separation between the bursts. Because the primary aim of the XMM-Newton observations was the study of the bursts, the EPIC-pn detector was operated in timing mode, which means that imaging is made only in one dimension, along the RAWX axis. Along the row direction (RAWY axis), data from a predefined area on one CCD chip are collapsed into a one-dimensional row for a fast read-out. Then source photons are extracted between RAWX values 30 – 45 and background photons are extracted between rows 2 – 16, as recommended by the standard procedure.
We produced pn lightcurves mainly to remove the burst intervals and to extract the spectra of the persistent part of the lightcurve. In the first observation nine bursts we detected, in the second observation seven bursts. We plot the burst profiles of these 16 bursts in Fig. 2.2. We estimate a mean duration of about 300 s for the bursts, and we removed for each burst 50 s before the peak to 250 s after it. Recently in’t Zand et al. (2009) suggested a mean duration of about 1 ks for the bursts, but they also argued that after the first 100 s the inferred emission decreases sharply by at least one order of magnitude, contributing only about 3% to the fluence in the burst. After 250 s the flux of the burst has decreased by almost two orders of magnitude and its profile merges with the persistent lightcurve. Thus, by removing 300 s for each burst, we retain less than \( \sim 1\% \) burst emission, which is negligible compared to the persistent emission.

We processed the RGS data with the SAS task \texttt{rgsproc}. We produced the lightcurves for the background in CCD9 following the XMM-SAS guide\(^1\) in order to remove soft proton flares and spurious events. We created good time intervals (GTI) by removing intervals with count rates higher than 0.5 \( \text{s}^{-1} \). We reprocessed the data again with \texttt{rgsproc} by filtering them with the GTI for background screening and bursts removal. We extracted response matrices and spectra for the two observations. The final net exposure times are reported in Table 5.1.

Our analysis focuses on the \( 7 – 31 \, \text{Å} \) (0.4 – 1.77 keV) first order spectra of the RGS detector. In order to fit the spectral continuum properly, we also use the 0.5 – 10 keV EPIC spectra of both observations. We performed the spectral analysis with SPEX\(^2\) version 2.01.05 (Kaastra et al. 1996). We scaled the elemental abundances to the protosolar abundances of Lodders (2003): \( \text{N/H} = 7.943 \times 10^{-5}, \text{O/H} = 5.754 \times 10^{-4}, \text{Ne/H} = 8.912 \times 10^{-5}, \text{Mg/H} = 4.169 \times 10^{-5}, \text{Fe/H} = 3.467 \times 10^{-5} \). We use the C-statistic throughout the paper and adopt 1\( \sigma \) errors.

\subsection*{2.3 Spectral modeling}

The first step of the spectral analysis consists of the determination of the continuum emission and the dominant absorption component. The best way to do this is to fit the spectra of RGS and EPIC-pn simultaneously. The XMM-\textit{Newton} cross-calibration is very complex, not only because of the different energy bands, but mainly because of their different features: RGS is sensitive in the soft X-ray energies with high spectral resolution, showing narrow absorption features, while pn has a low spectral resolution, therefore blurring the absorption features seen with RGS. EPIC-pn has a higher count rate compared to RGS and a broader energy band. The original RGS spectra are binned by a factor of 10 in this simultaneous fit. This is necessary to temporarily remove the narrow features due to the absorption lines. The pn spectra are resampled in bins of about 1/3 of the spectral resolution (FWHM \( \sim 50 – 150 \, \text{eV} \) between 0.5 – 10 keV), which is the optimal binning for most spectra.

A better local fit for absorption edges and lines is obtained from a separate RGS fit. In the RGS local fit we rebin the spectra only by a factor of two, i.e. about 1/3 FWHM.

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\(^1\)http://heasarc.nasa.gov/docs/xmm/abc/  
\(^2\)www.sron.nl/spex
Figure 2.1: Lightcurves of the first (left) and the second (right) observation with RGS1. Intervals with high background have already been taken out. The bursts are still shown for displaying purpose, but their contribution to the spectra are removed as described in the text. The plot shows the quasi-periodicity of the bursts and illustrates why GS 1826–238 is called the ‘clock-burster’ LMXB (Ubertini et al. 1999).

Figure 2.2: Mean profile of the bursts in the RGS lightcurve of the first observation. The zero point of the timescale is centered on the burst profile peak. The red line represents the mean count rate of the 2 ks around the peaks.
(the first order RGS spectra provide a resolution of 0.06–0.07 Å). This gives at least 10 counts/bin and a bin size of about 0.02 Å.

2.3.1 Simultaneous EPIC–RGS fits

At first we followed the spectral modeling of Thompson et al. (2008). The continuum spectrum is modeled by emission from a blackbody and two comptonization models. The blackbody component arises from the thermal emission of the accretion disk around the neutron star. The first comptonization component (hereafter C1) describes the energy gain of the disk soft photons by scattering in the accretion disk corona. The second comptonization component C2 corresponds to scattered seed photons originating from regions closer to the NS surface, i.e. the boundary layer. Thompson et al. (2008) applied a neutral absorber to the continuum mentioned above and fitted XMM-Newton, Chandra, and RXTE data. For this purpose we used the absm model in SPEX: the model calculates the continuum transmission of neutral gas with cosmic abundances as published by Morrison & McCammon (1983). In our case the same model does not give a satisfactory fit, especially around the neon and oxygen edges, and cannot fit the O I line. This could be expected because the Morrison & McCammon (1983) model does not take into account the absorption lines and the possible variations in the abundances. Therefore we replace the absm component with a hot component, which describes the transmission through a layer of collisionally ionized plasma. At low temperatures it calculates the absorption of (almost) neutral gas (for further information see the SPEX manual). We left the temperature and the O, Ne, Mg, and Fe abundances of this absorber free in the fit. In the fits we ignored two small regions (17.2 – 17.7 Å and 22.7 – 23.2 Å), close to the iron and oxygen edges respectively. The presence of dust and molecules affects the fine structure of the edge, thus these regions will be analyzed with more complex models in Sect. 2.3.2. However, the ISM abundances were determined by the depth of the absorption edges, thus ignoring these small regions we could still constrain the abundances of these elements (Kaastra et al. 2009). Indeed, in Sect. 5.5.4 and Table 2.6 we will validate this assumption. We obtained a good fit with C-stat/dof$^3$ = 2451/1705 and 2579/1710 in the two observations (see Fig. 2.3). The parameters for both observations are listed in Table 4.1. We call this simple model, where the ISM is modeled with one (neutral) gas component, Model A. The abundances mostly agree between the two observations, but they are not reliable. In Sects. 4.4.2 and 5.5.4 we show that the RGS fit provides a column density higher by 10%, which significantly changes the abundance estimates. There are also small differences in the continuum parameters, such as the electron temperatures. Indeed we find different temperatures for both comptonization components (see Table 4.1). These small deviations affect the broadband spectral slope and forbid to fit the two EPIC-pn observations simultaneously, while this is possible with the RGS spectra.

We also tested alternative continuum models in order to show that the adopted model is the best one. Thompson et al. (2008) showed that the spectral modeling of GS 1826–238 can be done with other continuum models: 1) blackbody emission plus

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$^3$Here and hereafter dof means degrees of freedom.
Table 2.2: EPIC–RGS spectral fits to the persistent emission. Abundances are relative to the protosolar values of Lodders (2003). Fluxes are derived in the 0.3-10 keV band. We also report the weighted averages between the two observations. See also Fig. 2.3.

<table>
<thead>
<tr>
<th>Par / component</th>
<th>OBS 1</th>
<th>OBS 2</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorber</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_H$ (10$^{25}$ m$^{-2}$)</td>
<td>3.65 ± 0.05</td>
<td>3.68 ± 0.04</td>
<td>3.67 ± 0.03</td>
</tr>
<tr>
<td>$kT$ (10$^{-4}$ keV)</td>
<td>7.07 ± 0.10</td>
<td>7.22 ± 0.09</td>
<td>7.15 ± 0.07</td>
</tr>
<tr>
<td>O</td>
<td>1.471 ± 0.008</td>
<td>1.403 ± 0.008</td>
<td>1.437 ± 0.006</td>
</tr>
<tr>
<td>Ne</td>
<td>2.72 ± 0.04</td>
<td>2.64 ± 0.04</td>
<td>2.68 ± 0.03</td>
</tr>
<tr>
<td>Mg</td>
<td>0.81 ± 0.09</td>
<td>0.80 ± 0.09</td>
<td>0.80 ± 0.06</td>
</tr>
<tr>
<td>Fe</td>
<td>1.90 ± 0.03</td>
<td>2.01 ± 0.02</td>
<td>1.98 ± 0.02</td>
</tr>
<tr>
<td>blackbody flux ($10^{-13}$ W m$^{-2}$)</td>
<td>0.65 ± 0.10</td>
<td>0.55 ± 0.03</td>
<td>0.56 ± 0.03</td>
</tr>
<tr>
<td>$kT_{bb}$ (keV)</td>
<td>0.170 ± 0.002</td>
<td>0.167 ± 0.002</td>
<td>0.168 ± 0.001</td>
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<tr>
<td>CI comptonization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flux ($10^{-13}$ W m$^{-2}$)</td>
<td>7.8 ± 0.3</td>
<td>7.7 ± 0.3</td>
<td>7.75 ± 0.21</td>
</tr>
<tr>
<td>$kT_s$ (keV)</td>
<td>0.25 ± 0.02</td>
<td>0.24 ± 0.01</td>
<td>0.24 ± 0.01</td>
</tr>
<tr>
<td>$kT_e$ (keV)</td>
<td>2.07 ± 0.05</td>
<td>2.38 ± 0.06</td>
<td>2.20 ± 0.04</td>
</tr>
<tr>
<td>$\tau$</td>
<td>11.0 ± 0.6</td>
<td>9.3 ± 0.4</td>
<td>9.8 ± 0.3</td>
</tr>
<tr>
<td>C2 comptonization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flux ($10^{-13}$ W m$^{-2}$)</td>
<td>0.9 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.75 ± 0.07</td>
</tr>
<tr>
<td>$kT_s$ (keV)</td>
<td>0.50 ± 0.01</td>
<td>0.54 ± 0.01</td>
<td>0.52 ± 0.01</td>
</tr>
<tr>
<td>$kT_e$ (keV)</td>
<td>9.4 ± 0.8</td>
<td>4.6 ± 0.5</td>
<td>5.9 ± 0.4</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$\leq 0.5$</td>
<td>$\leq 0.7$</td>
<td>-</td>
</tr>
<tr>
<td>C$_{stat}$/dof</td>
<td>2451/1705</td>
<td>2579/1710</td>
<td>-</td>
</tr>
</tbody>
</table>

a single comptonization component; 2) blackbody emission plus a cut-off powerlaw; 3) double comptonization plus a disk blackbody; 4) two comptonization components. We tested them on both spectra, but report here only the results for the first spectrum. The results for the other observation are similar. The models (1) and (2) give similar results, but with C-stat/dof = 3000/1709 the fit is worse than for our adopted Model A. Model (3) gives even worse fits. The final alternative model (4) gives an intermediate result C-stat/dof = 2625/1707.

2.3.2 The high-resolution RGS spectra

In Fig. 2.4 we plot the RGS spectrum of the persistent emission in the first and second observation. Several interesting features can be recognized. At 23.1 Å we see the absorption edge of the interstellar neutral oxygen, while the O I line is clearly visible at 23.5 Å. There is also a broad absorption feature close to the oxygen edge, which is clearly seen in the fits residuals, see Sect. 2.3.2 for a dedicated discussion. The K-edge of neon and L-edge of iron are easily recognized at 14.3 Å and 17.5 Å, respectively. We fitted the RGS spectra of the two observations simultaneously with Model A, freezing
Figure 2.3: Simultaneous RGS–EPIC best fits of the first (top) and the second (bottom) observations. The model used is Model A (see Sect. 2.3.1 and Table 4.1). The upper panels show from top to bottom the EPIC and RGS spectrum, respectively. The lower panels show the fit residuals (dark points with small error bars: EPIC). The dips in the count spectrum of the RGS correspond to bad columns in the RGS with lower sensitivity.
2.3 Spectral modeling

the shape of the continuum emission and leaving as free parameters the normalizations of the emission components and the parameters of the absorber. In the fits we still ignored the two small regions (17.2 – 17.7 Å and 22.7 – 23.2 Å), close to the iron and oxygen edges respectively (see Sect. 2.3.2 for the dedicated analysis). The results of the RGS spectral fits are shown in Table 2.3 and are referred to Model A. We also report the results of the fits obtained for each observation: the agreement between the parameters validates the simultaneous spectral fit. As expected, the residuals (Fig. 2.4) show large deviations in the spectral regions that we have temporarily removed: \( \sim 4\sigma \) and \( \sim 3\sigma \) near 17.4 Å and 23 Å, respectively. These features cannot be modeled with a pure-gas model and require the introduction of dust and molecular components in our model (see Sect. 2.3.2).

The neutral gas

The fits obtained with a simple model (a single gas component for the ISM) show that the ISM can be initially modeled with cold gas (see Table 4.1 and 2.3, Model A). It has a mean temperature of \( kT \sim 6 \times 10^{-4} \) keV, i.e. about 7000 K, and provides the bulk of the warm atomic gas anticipated in the introduction. It is almost neutral, except for iron and magnesium: Mg II contributes 30% to the total magnesium column density, while Fe II accounts for 20% of the iron. A precise measure of the ratios Mg II/Mg I and Fe II/Fe I for our spectra is not possible. Near the magnesium edge the spectrum is noisy and the Mg I and Mg II edges are close, at 9.48 Å and 9.30 Å respectively, while near the iron edge the lines are unresolved and there is also a contribution from dust that affects the edge structure (see Sect. 2.3.2). However, the total magnesium and iron column densities are estimated taking into account the jump across the respective edges, and they will not be affected by these problems. As expected, the RGS spectral fits provide a different \( N_{\text{H}} \) value than the simultaneous EPIC–RGS fit, because of the imperfect EPIC–RGS cross-calibration and the low resolution of EPIC, that smooth the absorption features (see Fig. 2.3).

The ionized gas

The fit residuals near 21.6 Å and 23.35 Å (see Fig. 2.4), where we should expect the 1s-2p transitions of O VII and O II respectively, suggest the presence of additional weak absorption features. Other weak features are found near 13.4 Å and 14.6 Å, close to the theoretical Ne IX and Ne II wavelengths. We deal separately with the different ionization states.

At first we made a fit to the RGS spectra adding columns of O II and Ne II to our model through a slab component. The slab model calculates the transmission of a layer of plasma with arbitrary composition. Free parameters are the intrinsic velocity dispersion and the column densities of the individual ions (Kaastra et al. 1996). The fits improve significantly: by fitting the two RGS observations simultaneously we get \( \Delta C\text{-stat} \sim 130 \). The velocity dispersion is not well constrained (\( \sigma_V = 50 \pm 15 \) km s\(^{-1}\)). The average ion columns are \( 1.2 \pm 0.4 \times 10^{21} \) m\(^{-2}\) (O II) and \( 2.4 \pm 0.4 \times 10^{21} \) m\(^{-2}\) (Ne II), while the cold gas gives \( 3.05 \pm 0.15 \times 10^{21} \) m\(^{-2}\) (O I) and \( 6.7 \pm 0.3 \times 10^{21} \) m\(^{-2}\) (Ne I).
Figure 2.4: Continuum best-fit to the RGS spectrum of the first (black) and the second (orange) observation. Here we use the simple model used for EPIC–RGS fits (see Sect. 2.3.1). In the fits we excluded two small regions near the O I K-edge and the Fe I L-edge (see Sect. 4.4.2), which are indicated by two red horizontal strips in the top panel. See Sect. 2.3.2 for the detailed analysis. The results of the fits are shown in Table 2.3, they refer to model A.

In second instance we add another slab component to take into account the contribution by the hot gas. The columns are $1.1 \pm 0.5 \times 10^{20}$ m$^{-2}$ (both O VII and O VIII) and $3.5 \pm 2.5 \times 10^{19}$ m$^{-2}$ (Ne IX). The addition of the hot gas provides $\Delta C$-stat = 30, which is significantly less than the improvement we obtained by adding the weakly ionized gas. Moreover we can only put an upper limit to the velocity dispersion of the hot ionized gas ($250$ km s$^{-1}$).

However, in order to take care of every absorption feature created by all ions in the warm-hot phases and to deal with physical models, we substituted the two slab components with two hot components. We coupled the elemental abundances of the warm-hot components to those of the cold gas, assuming all ISM phases have the same abundances. This is a reasonable assumption, especially for the warm (low-ionization) ionized gas, as its temperature is not too different from the temperature of warm neutral gas. The additional free parameters are the hydrogen column density, the temperature and the velocity dispersion. In summary, the additional warm and hot phases give an average improvement of $\Delta C$-stat $\sim 80$ for only six free parameters added. We
label such a three-gas model as Model B and display all results in Table 2.3. We plot the individual absorption edges of O, Fe, Ne and Mg in Figs. 2.5, 2.6, 2.7 and 2.8, respectively. We discuss these results in Sect. 5.5.2. The predicted deviations near the oxygen and iron edges, clearly seen in Fig. 2.5 and 2.6, still confirm that pure interstellar gas cannot reproduce all the absorption features and that we need to take into account different states of matter, such as solids.

Finally, we also considered the model where the cold gas component is forced to be neutral by freezing its temperature to $5 \times 10^{-4}$ keV, i.e. 5 800 K. In this case, we got an almost equal fit (C-stat/dof = 4466/3227), with the exception that the warm component has a significantly lower temperature ($\sim 1.4 \times 10^{-3}$ keV, i.e. 10 – 20 000 K), to account for the O II that in our nominal fit is partially produced by the cold component. This temperature value is more representative than our previous value of $5.4 \times 10^{-3}$ keV for the warm ionized gas in the ISM (Ferrière 2001). However, both fits are acceptable, thus we report only results obtained with the cold-gas temperature as free parameter in Table 2.3.

### Table 2.3: RGS spectral fits to the persistent emission

(a) We give the separate fits for the two observations only for Model A in order to show that they are consistent within the errors and thus can be fitted together. C-Stat / dof (*) refers to the statistics obtained by including the wavelength ranges 17.2-17.7 Å and 22.7-23.2 Å, which in fits are ignored except in the case of the complete model. (b) All columns for the dabs and amol components are reported in units of $10^{21}$ m$^{-2}$. (c) Each amol component is displayed together with its molecular index as reported in Table A.1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Mod A (a)</th>
<th>Mod B</th>
<th>Mod C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OBS 1</td>
<td>OBS 2</td>
<td>OBS 1+2</td>
</tr>
<tr>
<td>Cold</td>
<td>$N_H$ ($10^{23}$ m$^{-2}$)</td>
<td>4.18 ± 0.01</td>
<td>4.22 ± 0.07</td>
<td>4.21 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>$kT$ (10 keV)</td>
<td>5.90 ± 0.14</td>
<td>6.13 ± 0.12</td>
<td>6.02 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>$\sigma_v$ (km s$^{-1}$)</td>
<td>27 ± 15</td>
<td>18 ± 6</td>
<td>13 ± 7</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>1.30 ± 0.02</td>
<td>1.29 ± 0.02</td>
<td>1.29 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Ne</td>
<td>2.08 ± 0.04</td>
<td>1.86 ± 0.07</td>
<td>1.95 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>Mg</td>
<td>2.27 ± 0.12</td>
<td>2.14 ± 0.16</td>
<td>2.21 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>1.39 ± 0.02</td>
<td>1.42 ± 0.06</td>
<td>1.39 ± 0.05</td>
</tr>
<tr>
<td>Warm</td>
<td>$N_H$ ($10^{23}$ m$^{-2}$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$kT$ (10 keV)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\sigma_v$ (km s$^{-1}$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hot</td>
<td>$N_H$ ($10^{23}$ m$^{-2}$)</td>
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<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>$kT$ (keV)</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\sigma_v$ (km s$^{-1}$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dabs (b)</td>
<td>$N_{Fe}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$N_{Mg}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Amol (b,c)</td>
<td>$N_0$ (i=14, Silicates)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$N_0$ (i=7, H$_2$O Ice)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$N_0$ (i=2, CO)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$N_0$ (i=23, Aluminates)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Statistics</td>
<td>C-Stat / dof</td>
<td>2239/1595</td>
<td>2170/1589</td>
<td>4587/3232</td>
</tr>
<tr>
<td></td>
<td>C-Stat / dof (*)</td>
<td>2930/1684</td>
<td>3040/1710</td>
<td>5757/3410</td>
</tr>
</tbody>
</table>
Figure 2.5: $^{1}O_{I}$ K-edge: data and Model B. Black and grey points refer to the first and second observation, respectively.

Figure 2.6: $^{2}Fe_{I}$ L-edge: data and Model B.
Figure 2.7: Ne I K-edge: data and Model B.

Figure 2.8: Mg I K-edge: data and Model B
Fine structures: Dust and molecules

Further important improvements to our fit are obtained by adding both dust and molecules to our multiphase gas model. We use here two recently added models of SPEX: *dabs* and *amol*, which are briefly described below. The transmission of dust is calculated by the *dabs* model in SPEX: it accounts for the self-shielding of X-ray photons by dust grains, but uses the edge and line structure for atomic gas. It was first used in the analysis of the Crab spectrum by Kaastra et al. (2009). It follows completely the dust treatment as described by Wilms et al. (2000) and is useful to estimate the dust-to-gas column ratio and the depletion factor for several elements. We assume the default values for the grain parameters because they are physically acceptable: the grains are assumed to be spherical and fluffy, with density $\rho = 1000 \text{ kg m}^{-3}$, grain radius $a$ between $a_{\text{min}} < a < a_{\text{max}}$, where $a_{\text{min}} = 0.025 \mu\text{m}$ and $a_{\text{max}} = 0.25 \mu\text{m}$, with a size distribution $dn/da \sim a^{-p}$ and $p = 3.5$ (Kaastra et al. 2009). Including the *dabs* component in our model, we obtain a significant improvement to the fit by requiring at least $\sim 90\%$ of iron to be confined in dust grains (see Table 2.3). Inside the iron edge the shielding effect of dust is stronger than its fine structure features, and thus the *dabs* component is suitable to fit the data. Indeed, the $\sim 4\sigma$ deviation at 17.4 Å (Fig. 2.6) and the $\sim 1\sigma$ deviation near 17.1 Å, due to the assumption of a pure-gas ISM, just disappear (see Fig. 2.9). Moreover, from the *dabs* model we derive $\sim 40\%$ of the oxygen to be bound in dust grains. Unfortunately, this model does not yield a good fit of the oxygen edge, where strong features due to molecules are present that are not taken into account by the *dabs* model.

A much larger improvement is obtained when we introduce molecules and minerals containing oxygen atoms. For the first time we used the *amol* model in SPEX to take into account bound forms of oxygen. The model currently takes into account the modified edge and line structure around the O K-edge using measured cross sections of various compounds, taken from the literature. More details about this model can be found in Appendix A. The *amol* model is very useful to constrain the local molecular features, but it does not account for the dust shielding effects. We tried 23 different types of compounds such as CO, N$_2$O, H$_2$O, ice, FeO and several minerals. The best fit is obtained by using a mixture of silicates, such as andradite, and water ice plus other molecules (see Fig. 2.10 and Table 2.4). This additional component removes the previous $3\sigma$ deviation of the pure-gas model between 22.7-23.0 Å inside the oxygen edge (Fig. 2.5). Finally we completed the dust model choosing the *amol* component for oxygen and *dabs* component for all the other depleted elements, such as iron and magnesium. The final gas+dust model describes the data much better than all previous models (see Fig. 2.9 and 2.10) and it allows us to estimate the dust-to-gas ratio. We label this model C and show the parameters in Table 2.3.

2.3.3 ISM model complexity

The spectral modeling indicates that in the line of sight towards our X-ray source the ISM is much more complex than simple neutral gas. The gas is rather structured in different phases and dust also consists of various compounds.
2.3 Spectral modeling

Figure 2.9: Iron edge: data and Model C.

Figure 2.10: Oxygen edge: data and Model C.
The gas consists of three components (see Table 2.3): cold gas with a temperature $kT \sim 5 \times 10^{-4}$ keV ($5.8 \times 10^3$ K), warm ionized gas with $kT \sim 1 - 5 \times 10^{-3}$ keV ($1 - 6 \times 10^4$ K) and hot ionized gas with $kT \sim 0.2$ keV ($\geq 2 \times 10^6$ K). The column densities $N_H$ of these three components span over 2 orders of magnitude: the cold gas accounts for $\sim 90 - 95\%$ of the total column $N_{H}^{\text{tot}}$, $N_{H}^{\text{warm}} \sim 5 - 10\%$ of $N_{H}^{\text{tot}}$, while the hot gas contributes $\sim 1\%$.

The warm component produces the low-ionization absorption lines of O II and O III, at 23.35 Å and 23.1 Å respectively (see Fig. 2.5). It also provides a better modeling of the neon edge (see Fig. 2.7). Using model B we estimate $N_{O II} = 2.0 \pm 0.5 \times 10^{21}$ m$^{-2}$ and $N_{O III} = 1.4 \pm 0.5 \times 10^{21}$ m$^{-2}$, respectively $\sim 7\%$ and $\sim 5\%$ of the total oxygen column. However, the derived column density of the warm ionized gas is affected by the presence of dust and molecules in the line of sight. Indeed, the absorption features that we see near 23.35 Å and 23.1 Å are contaminated by dust and molecule effects. Contributions from dust and molecules (Model C in Table 2.3) are confirmed by the improvements to the fit (see also Fig. 2.9 and 2.10), and the column density of the warm gas is finally reduced to about 5\% of the full gas column (see Table 2.4).

The column density of hot gas is about two orders of magnitude lower than the cold gas column and its temperature is around two million K. As expected, the hotter gas has a higher velocity dispersion (see Table 2.3). The hot gas model gives a good fit of the O VII absorption line at 21.6 Å, together with the small feature at 13.4 Å produced by Ne IX.

According to the analysis of the oxygen edge, the solid phase of the ISM towards GS 1826–238 consists of a mixture of minerals (such as andradite silicates) and traces of CO and water ice. We cannot yet distinguish between amorphous and crystalline phases. As reported in Table 2.4 the bulk of the oxygen, $\sim 90\%$, appears to be in the gas phase, while the remaining $\sim 10\%$ is made mostly of solids, such as silicates and water ice. Obviously, there could be substances able to reproduce these features in the spectrum other than our few dozen test molecules. For the iron, instead, we obtain a different composition: at least $\sim 90\%$ of Fe appears to be bound in dust grains. In our dust model we assume a depletion factor of 0.8 for magnesium, as suggested by Wilms et al. (2000). The derived gas ($2.0 \pm 0.4 \times 10^{21}$ m$^{-2}$) and dust ($2.3 \pm 0.1 \times 10^{21}$ m$^{-2}$) column densities for the Mg are identical within the errors (see also Table 2.3).

### 2.3.4 ISM abundances

We estimated the abundances of Mg, Ne, Fe, O, and N (Table 2.5). The column density of each element refers to the sum of the contributions from all gas and dust phases. The abundances do not differ significantly between the two observations (see Table 2.3). This is expected if the absorption is mainly caused by the interstellar medium, because the ISM is stable on short timescales. The zero shift of the O I line, the position of the O, Fe, Ne, and Mg edges (see Fig. 2.5 to 2.10) and the low velocity dispersion suggest that the absorber matter is a mixture of gas and dust without outflows or inflows, not broadened owing to Keplerian motion around the X-ray source. This is also consistent with an ISM origin. For a more detailed discussion on the abundances and comparisons with previous work see Sect. 2.4.3.
Table 2.4: Table of the contributions to the oxygen column-density. \((a)\) \% of \(N_O^n\) represents the contribution of each constituent to the respective phase. \((b)\) \% of \(N_O\) give the contribution of the different phases to the total oxygen column density. See also Sect. 2.3.2 and Fig. 2.11 for the transmission of the main compounds.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Constituent</th>
<th>(N_O (10^{22} \text{ m}^{-2}))</th>
<th>% of (N_O^n (a))</th>
<th>% of (N_O (b))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>O I</td>
<td>2.7 ± 0.1</td>
<td>94 ± 4</td>
<td>90 ± 6</td>
</tr>
<tr>
<td></td>
<td>O II, O III, O IV</td>
<td>0.10 ± 0.05</td>
<td>4 ± 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O VII, O VIII</td>
<td>0.05 ± 0.01</td>
<td>2.0 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>Silicates</td>
<td>0.25 ± 0.05</td>
<td>85 − 100</td>
<td>10 ± 2</td>
</tr>
<tr>
<td></td>
<td>Aluminates</td>
<td>&lt; 0.04</td>
<td>0 − 15</td>
<td></td>
</tr>
<tr>
<td>Molecules</td>
<td>(\text{H}_2\text{O} \text{ ice})</td>
<td>&lt; 0.07</td>
<td>~ 65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>&lt; 0.04</td>
<td>~ 35</td>
<td>0 − 2</td>
</tr>
</tbody>
</table>

Figure 2.11: Transmission near the O I K-edge. The model used is Mod C (see Sect. 2.3.2, Table 2.3 and 2.6). Both cold-gas and entire-ISM transmission is multiplied by a factor of 4 for displaying purpose.
Table 2.5: Average ISM abundances in units of the protosolar values (Lodders 2003) and calculated by summing contribution from all ISM phases. (a) Model C, gas + dust. (b) Kaastra et al. (2009) Model B, gas + dust. (c) Yao et al. (2009a). (d) Juett et al. (2006). (e) Estimated through a local fit in the 27-33 Å range.

<table>
<thead>
<tr>
<th>X</th>
<th>O</th>
<th>Ne</th>
<th>Mg</th>
<th>Fe</th>
<th>N (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS 1826-238</td>
<td>1.23 ± 0.05</td>
<td>1.75 ± 0.11</td>
<td>2.45 ± 0.35</td>
<td>1.37 ± 0.17</td>
<td>2.4 ± 0.7</td>
</tr>
<tr>
<td>Crab (b)</td>
<td>1.030 ± 0.016</td>
<td>1.72 ± 0.11</td>
<td>0.85 ± 0.21</td>
<td>0.78 ± 0.05</td>
<td>1.01 ± 0.09</td>
</tr>
<tr>
<td>Cyg X-2 (c)</td>
<td>0.6 – 0.8</td>
<td>0.8 – 1.1</td>
<td>0.6 – 1.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4U 1820-303</td>
<td>0.7 – 1.1</td>
<td>1.1 – 2.0</td>
<td>-</td>
<td>0.3 – 0.8</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.6: I onic column densities of oxygen in 10^{22} m^{-2}. (a) Mono-phase gas (Table 2.3 for the simultaneous EPIC-RGS fit). (b) Three-phases gas (Table 2.3). (c) Gas + dust model (see Table 2.4). The agreement between the oxygen column densities estimated with different models validates our method.

<table>
<thead>
<tr>
<th>X</th>
<th>Mod A_{sim} (a)</th>
<th>Mod A (a)</th>
<th>Mod B (b)</th>
<th>Mod C (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O I</td>
<td>3.0</td>
<td>3.1</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>O II, O III, O IV</td>
<td>≡ 0</td>
<td>≡ 0</td>
<td>0.35</td>
<td>0.1</td>
</tr>
<tr>
<td>O VII, O VIII</td>
<td>≡ 0</td>
<td>≡ 0</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Dust</td>
<td>≡ 0</td>
<td>≡ 0</td>
<td>≡ 0</td>
<td>0.35</td>
</tr>
<tr>
<td>Total N$_O$</td>
<td>3.0</td>
<td>3.1</td>
<td>3.3</td>
<td>3.2</td>
</tr>
</tbody>
</table>

A separate analysis is required for the nitrogen edge at 30.8 Å. Indeed, at wavelengths higher than 29 Å the source flux decreases significantly and is comparable to the background. Thus, the spectrum around the N I K-edge is noisy and the N I column density has a large uncertainty. We decided to freeze the continuum parameters and try either a broadband fit to the range 7-33 Å or a local fit between 27-33 Å. The abundance estimates are consistent within the error. Their average is reported in Table 2.5.

2.4 Discussion

2.4.1 The continuum

Our analysis shows that the persistent state of the low-mass X-ray binary GS 1826–238 is well represented by a double comptonization (C1+C2) plus a blackbody (BB) emission component, all three absorbed by the interstellar medium composed of a three-phases gas, dust and molecules (see Table 4.1 and 2.3). In both observations the fits
agree: all the ISM parameters appear to be fully consistent, thus we can discuss the results from the simultaneous fit of the high-resolution RGS data.

### 2.4.2 ISM structure

In Sect. 5.5.2 we showed that in our line of sight the ISM has a clear multiphase structure. There are media with different ionization states, dust grains, and molecules. As confirmed by Fig. 2.11, the bulk of the matter responsible for X-ray absorption is found in the form of cold gas with a temperature $\sim 7000$ K and low-velocity dispersion ($\sigma_v \lesssim 13$ km s$^{-1}$). At this temperature the gas is almost neutral: only iron and magnesium are partially ionized. Part of the cold matter is found in solid compounds, such as dust grains and molecules. Most of the iron is bound in dust grains. About 10% of the oxygen is found in compounds: the silicates contribute up to $\sim 80\%$ of this phase, while the remaining fraction consists of a mixture of other oxides (such as iron aluminates) together with ices and CO molecules in similar quantities (see Table 2.4). The best fit is obtained using as compound the andradite silicate $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$, but we need higher signal-to-noise data to distinguish among the different silicates, because also olivine and pyroxene are good candidates. Moreover, at the present stage our model does not take into account simultaneously the shielding and fine structure effects of oxygen compounds, thus the fraction of oxygen bound in solids could be higher, e.g. up to 40% (see Sect. 2.3.2). However, we are working to the development of models that take into account all the possible effects and we postpone a deeper analysis of the oxygen dust phase to a forthcoming paper.

About 5% of the gas is ionized (see Mod C in Table 2.3). Most of it is a warm plasma with $T \sim 10 - 50,000$ K. It has a low-ionization degree and accounts for the interstellar $\text{O}$ II and $\text{O}$ III. Only 1-2% of the ISM gas appears to be highly ionized. Such a hot plasma reaches temperatures of $\sim 2 \times 10^6$ K and contributes to all $\text{O}$ VII and $\text{O}$ VIII present in the ISM. As we expect, the higher the temperature of the gas phase, the higher its velocity dispersion. Unfortunately the velocity dispersion is not well constrained, especially for the hot ionized gas. This is not surprising because the lines are unresolved.

### 2.4.3 Comparison with previous results

**ISM constituents**

The average total column density of the multi-phase gas we estimate is about $(4.14 \pm 0.07) \times 10^{25}$ m$^{-2}$. This is not consistent with the value of $(3.19 \pm 0.01) \times 10^{25}$ m$^{-2}$ found by Thompson et al. (2008). They combined data from Chandra, XMM-Newton and RXTE in the $0.5-100$ keV band, but we know that the bulk of the absorption is at lower energy. Instead we have used both EPIC and RGS data. The latter detector has a higher spectral resolution between $0.3 - 2$ keV and allows us to better estimate the absorption column. Also, Thompson et al. (2008) used the Morrison & McCammon (1983) model to fit the absorbing medium, which takes into account only contribution by cold neutral gas. In Sect. 2.3.1 we have shown that this model is not optimal, because it does not include lines. Furthermore, abundances and temperature cannot be free parameters. Instead
our estimate of $N_H$ is obtained by summing the contribution from all phases of the gas and by accounting for all absorption features found in the spectrum.

The multiphase structure of the ISM that we constrained is consistent with recent results (Ferrière 2001; Yao & Wang 2006; Yao et al. 2009a). First of all, there is a good agreement in the fractions between the cold, warm, and hot phases of the gas. In particular the estimated amount of O VII, $\sim 1.6 \times 10^{20} \text{ m}^{-2}$, is fully consistent with the value found by Yao & Wang (2006) by fitting both O VII 1s–2p and 1s–3p lines in the spectrum of 4U 1820–303, which is another LMXB near the center of the Galaxy. The hot gas accounts for 1–2% of the total column density and represents the average fraction of hot plasma in the Galaxy. Indeed it agrees with previous estimates and can be fully explained by the heating of supernovae (McCammon & Sanders 1990b). The velocity dispersion $\sigma_v$ estimates agree with recent work. Yao & Wang (2006) combined oxygen and neon ionization lines in the Chandra spectrum of the LMXB 4U 1820–303, obtaining $\sigma_v < 350 \text{ km s}^{-1}$. Juett et al. (2004) found $\sigma_v < 200 \text{ km s}^{-1}$ from oxygen lines fits to the Chandra spectra of several LMXBs.

Moreover, we found clear indications of dust depletion in some heavy elements, such as oxygen, iron, and magnesium. According to the different dust models that we used (dabs and dabs+amol), we find $\sim 50\%$ of Mg, more than 90% of Fe and 10–40% of oxygen in the form of dust grains and molecular compounds. These results are mostly consistent with previous estimates (Wilms et al. 2000; Kaasstra et al. 2009). The iron dust-to-gas ratio found towards GS 1826–238 is among the highest measured in the Galaxy. Williams & Taylor (1996) showed that the higher the density of a molecular cloud, the higher is the probability of forming dust and molecules from gas particles. Thus the higher dust-to-gas ratio we estimated towards the center of the Galaxy suggests high-density regions.

The presence of silicates and ice in the ISM, constrained by the O I K-edge analysis, is supported by other work. Paerels et al. (2001) found similar features within 22.7–23.0 Å in the spectrum of the LMXB X0614+091, and they argued that it should be due to iron oxides or oxygen generally bound in dust. Costantini et al. (2005) found indications of silicates such as olivine and pyroxene by modeling the feature of the scattering halo of Cyg X–2. Recently, de Vries & Costantini (2009) found evidence for EXAFS in the short-wavelength side of the oxygen edge in the spectrum of Sco X–1, and their results suggest the presence of amorphous water ice.

We have checked CO surveys (Dame et al. 2001) in order to test the presence of molecular clouds. There is no clear evidence for these clouds in our line of sight $(x, y)_{\text{GAL}} \sim (9.3^\circ, -6.1^\circ)$, while there is an important amount of diffuse dust (see also Schlegel et al. 1998). This is consistent with the fact that we can only put upper limits to ice and CO columns. Thus the absorption should arise from a solid phase consisting mostly of minerals.

**ISM abundances**

The abundances are displayed in Table 2.5, they are reported relative to the recommended protosolar values of Lodders (2003). We also show the abundances obtained by Juett et al. (2006) towards the LMXB 4U 1820–303, which like GS1826–238 is close
to the Galactic center. Even more interesting is the comparison with the abundances estimated by Kaastra et al. (2009) in the direction of the Crab nebula and those estimated by Yao et al. (2009a) towards Cyg X–2, which are two different lines of sight in our Galaxy (see the map in Fig. 5.1).

The derived abundances slightly depend on the model used: the pure-gas model and the complete gas+dust model yield different results on Ne, Fe, and Mg (Table 2.3). First, their abundances are more uncertain than the oxygen abundance. Secondly, Fe and Mg are the most depleted elements: as dust grains give rise to absorption features different from gas particles, modeling the edges of highly depleted elements provides different results if we account for dust effects or not. These deviations are probably intensified because we observed through a high-density region: here high metal depletion is expected (Williams & Taylor 1996).

All the heavy elements are over-abundant with respect to the protosolar values. Neon is over-abundant by a factor $\sim 1.7$, as found by Kaastra et al. (2009) in the XMM-Newton observations of the Crab nebula. The solar abundance of neon is probably under-estimated (see Lodders & Palme 2009), so our estimate may be not really different from the real solar value. As we will show in the next paragraph, the metallicity gradient could also be responsible for part of the Ne over-abundance.

The reason for the over-abundances of O, Fe, and Mg is rather different from the neon excess. First of all, we are able to measure both gas and dust contributions for O, Fe and Mg, without the risk of missing important fractions. Secondly, deviations in the abundances with respect to the average Galactic values are also due to their metallicity
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If $A(X)$ is the abundance of a certain element $X$ in the vicinity of GS 1826–238, we can write (see Esteban et al. 2005)

$$\frac{A(X)}{A(X)_{\odot}} = 10^{\alpha_X(D_{\odot} - D_{GS})},$$

where $D_{\odot}$ and $D_{GS}$ are the galactocentric radii of the Sun and GS 1826–238, respectively $\sim 8.5$ kpc and $\sim 2$ kpc; $\alpha_X$ is the abundance gradient of the element along the line of sight and $A(X)_{\odot}$ is its abundance near the Sun. In this way, we can compare our estimates of abundance changes with the values predicted by the gradient estimates. Unfortunately, the gradient estimates in the literature are quite uncertain and are available only for a limited range of radii, i.e. between 4-16 kpc (see Pedicelli et al. 2009). Thus we can trust only in the abundance changes in $4-5$ kpc along our line of sight.

Moreover, the column density estimated for each element refers to its integral along the line of sight, where we also expect a density increase towards the Galactic Center. Because the density increases towards the Galactic center, the predicted abundance at the galactocentric distance of GS 1826–238 should be close to the weighted average abundance along the sightline:

- Oxygen is over-abundant by about 20 – 30% (see Table 2.5). According to Esteban et al. (2005), the oxygen gradient is $\alpha_O = (-0.04 \pm 0.01)$ kpc$^{-1}$, which should provide an increment (equation 2.1) of at least $\sim 32\%$ in the oxygen abundance. This is consistent with our estimate.

- The iron abundance $\sim 1.20 - 1.54$ (see Table 2.5) almost agrees with the $\gtrsim 50\%$ increment derived by the accepted iron gradient in the Galactic disk $\alpha_{Fe} = (-0.06 \pm 0.02)$ kpc$^{-1}$ (Friel et al. 2002; Pedicelli et al. 2009).

- Neon is over-abundant by more than 70%. It is difficult to compare it with the Galactic gradient because this is quite uncertain, on average $\alpha_{Ne} = (-0.06 \pm 0.04)$ kpc$^{-1}$ (Simpson et al. 1995; Maciel & Quireza 1999). From equation (2.1) we predict a lower limit $A(\text{Ne}) \sim 1.3$. The sum of this a value to the revisited protosolar abundance ($\Delta A(\text{Ne}) \sim 30\%$, see Lodders & Palme 2009) provides $A(\text{Ne}) \sim 1.6$, which is fully consistent with our estimate. This result suggests that the neon over-abundance that we constrain is due to both the Galactic gradient and the previous under-estimate found in the literature.

- Nitrogen shows a steeper Galactic gradient of about $\sim -0.08$ kpc$^{-1}$ (Gummersbach et al. 1998), which provides $\Delta A(\text{N}) \sim 100\%$ (equation 2.1) and agrees with our estimate (see Table 2.5). Of course, both of them are quite uncertain and we are not able to provide more information.

- Also magnesium should be at least twice the protosolar value as we found (see Table 2.5). However, it is difficult to compare our result with the Mg Galactic gradient found in the literature, because the results differ widely in the literature (Rolleston et al. 2000). According to Gummersbach et al. (1998) $\alpha_{Mg} \sim -0.08$ kpc$^{-1}$, which together with equation (2.1) implies an abundance increment of at least 100%. This is fully consistent with what we found.
2.5 Conclusion

The iron and oxygen abundances towards 4U 1820–303 (Table 2.5) appear to disagree with our results despite its similar location near the Galactic center. Juett et al. (2006) attribute this low iron abundance to depletion into dust grains in the interstellar medium, and they also report that oxygen could be middle-depleted. In Sect. 2.3.2 we have shown that iron is among the most depleted elements in the ISM, oxygen is also partially depleted and a pure-gas model cannot reproduce all the ISM spectral features. This indicates that the differences between the Fe and O abundances are due to the capability of our gas+dust model to measure the contribution from solid phases, which are absent in the pure-gas model of Juett et al. (2004, 2006).

The Crab nebula is relatively close to the Solar System, i.e. \( \sim 2 \) kpc, but opposite to the Galactic Center (see Fig. 5.1). Thus we expect abundances close to the protosolar values of Lodders (2003), which is just what Kaastra et al. (2009) found.

The source LMXB Cyg X-2 is also far away from the center of the Galaxy and about 10 kpc away from the Sun. The abundances estimated for this source are lower than those measured towards the Crab and GS 1826–238 (see Table 2.5). This agrees with the assumed abundance gradients we have discussed.

In summary, the differences with respect to the protosolar abundances that we estimate are consistent with the literature. The increase of metallicity towards the center of the Galaxy should be due to evolutionary effects like supernovae explosions, which enrich the ISM with heavy elements, especially in the higher density region of the bulge and the disk of our Galaxy. A deeper analysis is required: we need to study more sources, even in the same region, and further improve our models in order to account for every contribution to the column densities.

2.5 Conclusion

We have presented a complete treatment of the interstellar medium towards the low-mass X-ray binary GS 1826–238, which is a bright X-ray source near the Galactic Center. We have shown that in the line of sight the ISM is composed of a complex mixture of a multi-phase gas, dust, and molecules.

The gas is almost neutral and the ionization degree is about 5%. Significant fractions of the column density of some heavy elements are in the form of molecules or dust grains: at least 10% of oxygen, 50% of magnesium, and 90% of iron. Such a solid phase should consist of a mixture of silicates (\( \gtrsim 60\% \)), CO (\( \lesssim 10\% \)), ice (\( \lesssim 20\% \)) and other iron oxides (\( \lesssim 10\% \)).

We have found over-abundances for all the elements for which we have been able to measure the individual column density. The Ne over-abundance that we estimate is consistent with other recent work in different lines of sight, such as towards the Crab (Kaastra et al. 2009), suggesting that the solar value is underestimated. However, our agreement with the predicted Ne gradient in the Galaxy is also consistent with an abundance increase owing to stellar evolution: towards the Galactic center there are high-density regions with evolved star that could have enriched the ISM with heavy elements such as neon.
Differently from the previous X-ray spectroscopy work, we have found over-abundances for oxygen (1.2), iron (1.4) and magnesium (2.4). These elements are also in the form of dust and molecules. Thus our estimates are partially due to the fact that we are also able to measure the contributions from the solid phase. The abundance of metals agrees with the metallicity gradients and shows the chemical inhomogeneity of the interstellar medium.

The diagnostic of the ISM constituents fits the predicted models for both its thermal and chemical structures, showing a good agreement with the current state of art (Ferrière 2001). The dust column is consistent with the multi-wavelength, X-ray versus IR, observations. All this supports our research method and justifies new observations and analyses of other sources in different lines of sight. These analyses provide indeed a better mapping of the ISM and a deeper study of its chemical composition, together with its role in the evolution of the entire Galaxy.

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A phenomenological model for the X-ray spectrum of nova V2491 Cygni

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Abstract

The X-ray flux of nova V2491 Cyg reached a maximum some forty days after optical maximum. The X-ray spectrum at that time, obtained with the RGS of XMM-Newton, shows deep, blue-shifted absorption by ions of a wide range of ionization. We show that the deep absorption lines of the X-ray spectrum at maximum, and those observed nine days later, are well described by a phenomenological model with emission from a central blackbody and from a collisionally ionized plasma (CIE). The blackbody spectrum (BB) is absorbed by three main highly ionized expanding shells; the CIE and BB are absorbed by cold circumstellar and interstellar matter that includes dust. The outflow density does not decrease monotonically with distance. The abundances of the shells indicate that they were ejected from an O-Ne white dwarf. We show that
the variations on time scales of hours in the X-ray spectrum are caused by a combination of variation in the central source and in the column density of the ionized shells. Our phenomenological model gives the best description so far of the supersoft X-ray spectrum of nova V2491 Cyg, but underpredicts, by a large factor, the optical and ultraviolet flux. The X-ray part of the spectrum must originate from a very different layer in the expanding envelope, presumably much closer to the white dwarf than the layers responsible for the optical/ultraviolet spectrum. This is confirmed by the absence of any correlation between the X-ray and UV/optical observed fluxes.

3.1 Introduction

The sensitivity to soft X-rays of the EXOSAT satellite enabled the first discovery of X-rays from a classical nova, GQ Mus, in April 1984 (Oegelman et al. 1984). The ROSAT satellite detected it almost eight years later, in February 1992, and found it to have a very soft blackbody-like spectrum with $kT_{\text{eff}} \sim 28$ eV (Oegelman et al. 1993). ROSAT observations of other novae in our galaxy showed that only a small fraction of novae are detected in X-rays (Oegelman et al. 1993; Orio et al. 2001).

The spectrum of GQ Mus is very soft, comparable to the spectra of a new class of supersoft X-ray sources (SSS) discovered with ROSAT in the Large Magellanic Cloud, with temperatures $\leq 100$ eV in blackbody fits to their spectra (Trümper et al. 1991; Greiner et al. 1991). The favored explanation for the X-ray spectra of the supersoft sources such as for GQ Mus is hydrogen burning at the surface of a white dwarf, of material accreted from a companion star. The class of supersoft X-ray sources shows a large variety, some sources being permanent and others transient, and with wide different types of companion stars (see review by Kahabka & van den Heuvel 1997). Observation campaigns with ROSAT, XMM-Newton and Chandra in M31 show that most of the supersoft sources are classical novae (Pietsch et al. 2005; Henze et al. 2010). Recently, Henze et al. (2011) argued that the high fraction of novae without detected SSS emission might be explained by the incomplete coverage.

The model fits of the supersoft X-ray spectra have become increasingly sophisticated over the years. Blackbody fits indicated high super-Eddington luminosities for the ROSAT sources. Heise et al. (1994) showed that the fit of local thermodynamic equilibrium (LTE) model atmospheres to the ROSAT data brought their bolometric luminosity below the Eddington limit for temperatures $\leq 60$ eV. For temperatures $\geq 100$eV, Hartmann & Heise (1997) showed that the differences between bolometric luminosities for ROSAT supersoft sources derived from blackbody, LTE and NLTE models are much smaller, the main difference being that NLTE models may give appreciable flux above 0.4 keV (i.e. in the ‘hard’ ROSAT band). A new level of sophistication is reached by Petz et al. (2005), who fit NLTE model spectra of expanding atmospheres, thus taking into account the outflow inherent in the nova phenomenon. Even the most sophisticated model fails to fit the observed continuum of the nova V4743 Sgr at $\lambda < 30$ Å, and also does not match the depth of the absorption lines (Fig. 3 of Petz et al. 2005; Rauch & Werner 2010). With regard to the X-ray spectra of V2491 Cyg, the best published atmosphere model does not reproduce the observed line velocities or the observed line
3.1 Introduction

depths, as clearly visible in Fig. 11 of Ness et al. (2011), for example in the N\textsuperscript{vii} 1s-2p line at 24.8 Å. Atmosphere models so far also fail to reproduce the wide range of ionization levels simultaneously present in the observed spectra: e.g. O\textsuperscript{v} to O\textsuperscript{viii} in V2491 Cyg (see Figs. 3.1-3.4 below).

What is the reason for this failure? If there are shocks in the expanding nova envelope, the assumption of a standard atmosphere whose density decreases monotonically outward, breaks down. The rapid X-ray variability observed in some novae indicates that the expanding envelope and/or the luminosity from the deeper layers are not stationary and/or not spherically symmetric, invalidating another assumption in atmosphere models. In this paper we therefore investigate a pilot model of a quite different nature, in which separate expanding shells absorb the spectrum of an underlying central source. In this first study, we describe the central source as a blackbody spectrum. We apply our simple model to the XMM-Newton RGS spectra obtained from the nova V2491 Cyg to investigate whether this model gives a better description of the continuum and line absorption; whether the short-term variability is due to changes in the source or in the absorption; and whether the model allows determining of the chemical abundances in the expanding envelope.

Nova V2491 Cyg was discovered on April 10, 2008, at $V = 7.7$ (Nakano et al. 2008). The optical flux declined from this peak in the course of the following months, interrupted by a brief second maximum at the end of April. Ultraviolet and X-ray fluxes of the V2491 Cyg were obtained with the Swift satellite: the ultraviolet flux declined in tandem with the optical flux (measured through May and June), whereas the X-ray luminosity rose from a marginal detection on April 11 to a peak more than a thousand times brighter some 40 days later (Page et al. 2010). Lightcurves of optical, ultraviolet and X-ray are shown in Fig. 4 of Page et al. (2010). In the Swift X-ray range (0.3-8 keV) the spectrum peaks strongly near 0.4-0.5 keV during the X-ray maximum and has a flatter (i.e. harder) energy distribution before and after X-ray maximum (see Fig. 3 of Page et al. 2010).

From a relation between maximum magnitude of novae and their rate of decline, a distance of 10.5 kpc has been estimated for V2491 Cyg by Helton et al. (2008). The optical flux was already declining during the first measurements, and therefore the actual flux maximum may have been higher than the flux of the first measurement: this would imply a smaller distance.

The interstellar reddening $E(B-V) = 0.43$ has been estimated from the ratio of the O\textsc{i} lines at 0.84 and 1.13 micron (Rudy et al. 2008), and may be converted into a hydrogen column $N_H = 2.4 \times 10^{25}$m$^2$ using the relation determined by Predehl & Schmitt (1995).

The X-ray spectra described in this paper were obtained with XMM-Newton just before the X-ray maximum, and some nine days later, when the X-ray flux had declined by an order of magnitude.

Our paper is structured as follows. In Section 2 we describe the XMM-Newton data and provide a brief description of the four spectra that we will analyze. In Section 3 we describe a basic model and apply it to the spectra. In Section 4 we discuss several variant models and their applications. In Section 5 we discuss our model fits and in Section 6 we summarize our conclusions and outline prospects for improvements to the models.
3.2 Data and brief description of the spectra

The data discussed in this paper were obtained during two observations with XMM-Newton, as described in Ness et al. (2011). The first observation started at day 39.86, measured from the initial optical discovery on 2008 April 10.73 UT, and lasted 39280 s. During this first observation the RGS countrate varied strongly: from about 15 cts/s during the first 7500 s it dropped to a minimum near 3 cts/s lasting some 6000 s, and then rose to a maximum of about 18 cts/s for the final 16000 s of the observation. We follow Ness et al. (2011) in defining three spectra for this first observation, spectrum A.1 obtained during the initial plateau; spectrum A.2 during the minimum flux; and spectrum A.3 during the final high-flux plateau, (see Fig. 3 of Ness et al. 2011). The second observation started on day 49.62, and showed a countrate that varied only mildly around 3 cts/s during the 31700 s observation. All data from this observation are collected in the fourth spectrum, spectrum B.

We analyzed the 7-38 Å (1.77-0.33 keV) first order spectra of the RGS detector, using SPEX version 2.02.03 (Kaastra et al. 1996).

We show the four spectra derived from the XMM-Newton RGS observations in Figs. 3.1-3.4 (see also Figs. 6 and 7 of Ness et al. 2011). The most prominent features are the neutral oxygen absorption edge near 23 Å with the corresponding 1s-2p absorption line at 23.5 Å. The neutral nitrogen 1s-2p absorption line near 31.2 Å is also visible, but the neutral iron L_{2} and L_{3} edges that one expects near 17.15 and 17.45 Å are weak. Ness et al. (2011) identify 1s-3p and 1s-4p lines of O^{VII} near these wavelengths. Indeed, absorption lines from O^{V} to O^{VIII} are detected, blueshifted with respect to the rest frame wavelength; examples include O^{VIII} near 19 Å, O^{VII} at 21.5 Å, and N^{VII} at 24.5 Å. The blueshift indicates that the absorbing matter is expanding, and the wide range of ionization levels indicates that several expansion shells are involved.

Lines of highly ionized neon and oxygen are also detected at the rest frame wavelengths; examples are Ne^{X} at 12.1 Å, Ne^{IX} at 13.4 Å, O^{VIII} at 19.0 Å, and O^{VII} at 21.6 Å. A strong feature is also seen near 29.3 Å, close to the forbidden N^{VI} line at 29.5 Å.

3.3 The basic model

As a first attempt to describe the spectrum \( F_\lambda \) we used a multi-component model which may be written symbolically as

\[
F_\lambda = \left( F_{\lambda, \text{BB}} \prod_{i=1}^{3} X_i + F_{\lambda, \text{C}} \right) \cdot X_g \cdot X_d .
\]  

(3.1)

The components in this model and their parameters are

- the blackbody flux \( F_{\lambda, \text{BB}}(R, T_{\text{eff}}) \) characterized by the radius \( R \) and effective temperature \( T_{\text{eff}} \),
- three photo-ionized absorbers \( X_i(N_{i,O}, \xi_i, v_i, \sigma_i, (A/O)_i) \), each characterized by the column density for oxygen \( N_{i,O} \), the ionization parameter \( \xi_i \), the outflow velocity
3.3 The basic model

Figure 3.1: Best fit to the first observation A.1 (see also Table 3.1). The rest-frame wavelengths of all main transitions are displayed.

Figure 3.2: Best fit to the second observation A.2.
Figure 3.3: Best fit to the third observation A.3.

Figure 3.4: Best fit to the fourth observation B.
3.3 The basic model

$v_i$, the velocity width $\sigma_i$, and the abundances of various elements with respect to oxygen $(A/O)_i$. The number of absorbers is in principle free: we added absorbers until the fit did not significantly improve anymore (as indicated by the $\Delta \chi^2$; see Table 3.1). In this case, this leads to at least three absorbers.

- the flux from a collisionally ionized plasma $F_{iC}(EM, T, \sigma_C, (A_{Ne})_C, (Mg/Ne)_C)$, characterized by the emission measure $EM \equiv \int n_e n_X dV$, the temperature $T$, the turbulent velocity $\sigma_C$, the neon abundance $(A_{Ne})_C$, and the abundance ratio of magnesium to neon $(Mg/Ne)_C$,

- the absorption by interstellar or circumstellar gas $X_g(N_H, T_g, A_g)$, characterized by the hydrogen column $N_H$, the temperature $T_g$, and the abundances for each element $A_g$, and

- the absorption by interstellar dust $X_d(N_{d,O})$, characterized by the column of oxygen in the dust $N_{d,O}$.

To correctly describe the interstellar absorption $X_g$ with high spectral resolution, we used the SPEX model *hot*, adjusting its temperature $T_g$ at a low value (near 1 eV), suitable for the (nearly) neutral component of the ISM. This model describes the transmission through a layer of collisionally ionized plasma. We give abundances of the ISM normalized on proto-solar values; here and in the following, when we refer to proto-solar values we use those given by Lodders & Palme (2009).

The detailed form of the Fe I edge near 17.2-17.7 Å and the O K edge near 22.7-23.2 Å may be affected by the presence of these elements in molecules in dust (Paerels et al. 2001). The absorption $X_d$ by such molecules is described in SPEX with *amol* (Pinto et al. 2010). In the spectra of V2491 Cyg, the iron feature is weak, and thus we only constrain oxygen compounds in the interstellar dust.

A highly ionized absorber $X_i$ is modeled in SPEX with the *xabs* model, which gives the transmission of a slab of photo-ionized material. Before this model is applied, one must compute the ionization levels, and for this we used version C08.00 of Cloudy (for a description of an earlier version, see Ferland et al. 1998). Cloudy computes the ionization balance of a gas for the ionization parameter $\xi \equiv L/(nr^2)$, a measure of the number of photons per particle (for a light source with luminosity $L$ at distance $r$ of the gas with number density $n$), and a given spectral energy distribution (SED). The form of the energy distribution is important, because a soft irradiating spectrum leads to a different ionization equilibrium than a hard irradiating spectrum with the same luminosity. The energy distribution that we used for V2491 Cyg is shown in Fig. 3.5. It has been computed through all available archival data from IR to X-ray energies: IR fluxes from Naik et al. (2009), optical from Hachisu & Kato (2009), UV and soft X-ray from Ness et al. (2011), and hard X-ray from Page et al. (2010). We have taken their fluxes and models in each wavelength band and corrected for the Galactic interstellar extinction by assuming a $N_H = 2.5 \times 10^{25}$ m$^{-2}$, which represents an average between our fits and those found in the literature. The total luminosity of this SED is $1.15 \times 10^{33}$ W, of which the X-rays, roughly described as a blackbody with the temperature of 110 eV (blue dash-dotted line in Fig. 3.5), contribute $6.23 \times 10^{32}$ W.
The abundances of the highly ionized absorber are obviously also important for calculating the ionization structure. To compute the ionization levels we used proto-solar abundances. In principle, once we determined the abundances of the highly ionized absorbers from our spectral fit, the computation of the ionization structure should be iterated for these new abundances. In this pilot study, however, we have not performed this iteration.

To limit the number of free parameters, we limited the number of independent abundances in the basic model as follows. The flux $F_{\lambda_C}$ of collisionally ionized plasma dominates only at wavelengths $\lambda < 15$ Å in the spectra of V2491 Cyg and at these wavelengths only magnesium and neon contribute to the emission. We determined the Mg and Ne abundances from this part of the spectrum, and assumed that the abundances thus determined for the collisionally ionized plasma are also valid for the highly ionized absorbers $X_i$. Conversely, we determined the column of O, and the number ratios of C, N, Si, S, Ar, Ca, Fe with respect to oxygen from the absorption lines of the highly ionized absorbers $X_i$, assuming that these ratios are the same for all three highly ionized absorbing shells. We then assumed that the ratios found for the highly ionized absorbing shells also apply to the collisionally ionized plasma.

The reason for listing abundances with respect to oxygen is that these are much better constrained by the observed spectrum than abundances with respect to hydrogen, because hydrogen only contributes to the X-ray spectrum as a source of free electrons. The ionized hydrogen of the hot nova shell only affects the spectral normalization, but
3.3 The basic model

not the shape in the RGS spectra.

3.3.1 Application to spectrum A.3

We applied the basic model first to the spectrum with the highest signal-to-noise ratio, spectrum A.3. To be able to use \( \chi^2 \) statistics, we binned the RGS data in bins of about 1/3 of the spectral resolution of \( \sim 0.065 \) Å of the first-order RGS spectrum. To ensure a minimum of 10 counts/bin we in addition rebinned the raw data at the shortest wavelengths. This led to rebinning by factors 10, 5 and 2 in the ranges 7-11 Å, 11-15 Å, and 15-38 Å, respectively.

In a first step we fit a preliminary model, in which we ignore the highly ionized absorption shells \( X_i \) and the dust absorption lines \( X_d \). This provided us with initial estimates for the blackbody and collisionally ionized plasma, which we then entered as starting values in the full model fitting. The value that we derived for the temperature of the collisionally ionized plasma was determined mostly from the spectrum at \( \lambda < 15 \) Å, and more specifically from the ratio between the Ne \( \text{IX} \) and Ne \( \text{X} \) 1s-2p lines in this region. For this reason we fixed the plasma temperature \( T \) in the full model fitting at the value found from the preliminary fit.

The resulting values of the parameters for the full model are listed in Table 3.1, and the resulting model spectrum is shown in Fig. 3.3.

The radius of the blackbody emitter, 17,600 km, is several times the radius of a white dwarf (which decreases from \( \approx 9,000 \) km for a 0.6 \( M_\odot \) white dwarf to \( \approx 3,000 \) km at 1.3 \( M_\odot \); see Eq.(27) of Nauenberg 1972, and Provencal et al. 2002). This implies that the photospheric surface lies in the expanding layers. With the temperature of \( 1.4 \times 10^6 \) K, the blackbody has a bolometric luminosity \( L_{BB} = 8.5 \times 10^{32} \) W.

To describe the high-ionization absorption lines, we required three distinct \( X_i \) components. An outflow with constant velocity and constant mass flux \( \dot{M} \), has \( n r^2 \propto \dot{M}/v \) and therefore \( \xi \) is constant with radius. If the velocity increases with radius, as in a homologous expansion, we expect \( \xi \) to increase with radius. This agrees with our finding that the shell with the highest ionization parameter \( \xi_i \) has the highest velocity. However, our finding that the shell with the intermediate velocity has the lowest \( \xi_i \) is puzzling. This result may be due to systematic errors in the velocities of weak shells 2 and 3, caused by the difficulty in separating the velocity dispersion and shift in the absorption lines of these relatively weak shells (see also Sect. 3.3.1).

The lines of \( \text{C VI} \), \( \text{Ar XVI} \) and \( \text{S XIV} \) are weak compared to the oxygen lines, and this results in number ratios \( \text{C/O} \), \( \text{Ar/O} \) and \( \text{S/O} \) much lower than solar. For Ca we can only give an upper limit to the Ca/O ratio. We estimated the hydrogen column by assuming a proto-solar O/H ratio.

The relative strengths of the \( \text{O VII} \gamma \) plus \( \text{Fe I} \) edge at 17.2-17.7 Å and the oxygen features at 22.7-23.2 Å indicate an Fe/O ratio lower than proto-solar. This suggests that Fe may be depleted by dust. Indeed, we prefer to describe the broad absorption feature at 22.7-23.3 Å with a dusty-molecule component of silicates plus a gaseous component of \( \text{O II} \), with about 10% of the total oxygen in each of these two components. The alternative explanation with low-ionization \( \text{O II-IV} \) in gaseous form only is less appealing because it requires a very high velocity dispersion.
Deviations

There are some features that limit the quality of the fit. Most of them show broad emission-like features and are much more relevant in the low-continuum spectra. Indeed, in the high-flux spectra these features are well hidden by both strong continuum and absorption lines. The strongest lines are at 18.4 Å, 19.0 Å, 19.2 Å, 21.5 Å, 21.9 Å, 26.5 Å, 27.5 Å, and 29.35 Å. Most of the emission lines are less blueshifted than the absorption line of the same transition, thus the emission should originate from a broader region of the shell. This would explain the whole line shape similar to a P Cygni profile. There are also a few absorption lines not reproduced by the model at 19.8 Å, 25.8 Å, 29.1 Å, and 29.7 Å, which have already been reported by Ness et al. (2011) as unidentified lines. These lines could represent an additional slower (−2000 km s⁻¹) expanding layer because their projected wavelengths are consistent with O V, Ca X III, Ar X III, and Fe XVI/Al XI transitions. However, as mentioned above, these absorption lines are so much weaker than the strong ones that the inclusion of an additional layer does not provide a significant improvement to the fit.

Systematic errors

In Table 3.1, only the relatively small statistical parameter errors are given, which are likely much smaller than the combined statistical plus systematic uncertainties. The statistical errors are a proxy for the quality data, while systematic uncertainties are the main limitation for the accuracy of our results. A few parameters are highly model-dependent or have a degenerate value. Both the velocity dispersion and the blueshift of the shell layers have this problem. The complexity of the absorption lines plus the presence of weak emission lines complicate the modeling because the different components could mix with each other. This can happen to the components that refer to the weak unresolved emission lines (layers 2 and 3). Thus, the conclusion of different expansion velocities in two low-ionization layers is less certain than, e.g., the fact that the highest-ionization layer has a higher velocity shift and broadening.

3.3.2 Application to Spectra A.1, A.2 and B

In fitting the other X-ray spectra of V2491 Cyg, which have somewhat lower signal-to-noise ratio, we fixed the velocity dispersion of the collisionally ionized plasma, as well as the (relative) abundances of this plasma, of the highly ionized absorbers $X_i$, and of the cold absorption component $X_g$ to the values determined for spectrum A.3. The resulting values of the other parameters are collected in Table 3.1, and the spectral fits are shown in Figs. 3.1, 3.2 and 3.4, respectively.

The blackbody radius of spectrum A.1 is similar to that of spectrum A.3, but the temperature is lower by a quarter, and as a result the bolometric luminosity is lower by 50%; within the RGS band the blackbody flux is lower by 60%. For the collisionally ionized plasma, the temperature is same in the spectrum A.1 as in spectrum A.3, but the emission measure, and therefore also the luminosity, is lower by 45% in the former. As regards the highly ionized absorption shells, all parameters are similar in
Table 3.1: RGS best-fit parameters to the four observations (see also Figs. 3.1, 3.2, 3.3, and 3.4). (a) The CIE temperature is kept frozen to the value estimated with a local fit to the 7 – 15 Å spectral range. (b) We can only provide an upper limit for Ca relative abundance. (c) All errors are statistical, systematic effects are not considered here (for further information see Sect 3.3.1).

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>A.1</th>
<th>A.2</th>
<th>A.3</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackbody</td>
<td>( R (10^7 \text{ m}) )</td>
<td>2.1 ± 0.2</td>
<td>1.0 ± 0.1</td>
<td>1.76 ± 0.03</td>
<td>0.19 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>( kT_{\text{eff}} ) (eV)</td>
<td>91 ± 1</td>
<td>81 ± 1</td>
<td>121 ± 2</td>
<td>95 ± 1</td>
</tr>
<tr>
<td></td>
<td>( L_{\text{RGS}} ) (10^{32} \text{ W})</td>
<td>2.20</td>
<td>0.23</td>
<td>5.70</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>( L_{\text{BOL}} ) (10^{32} \text{ W})</td>
<td>4.39</td>
<td>0.57</td>
<td>8.49</td>
<td>0.04</td>
</tr>
</tbody>
</table>

| CIE       | \( n_e \) (\text{m}^{-3}) | 5.6 ± 0.7 | 7.1 ± 0.7 | 9.6 ± 0.4 | 5.2 ± 0.4 |
|           | \( kT \) (keV) (a) | 0.39 ± 0.05 | 0.39 ± 0.05 | 0.37 ± 0.05 | 0.71 ± 0.05 |
|           | \( L_{\text{RGS}} \) (10^{38} \text{ W}) | 0.79 | 1.05 | 1.40 | 0.94 |
|           | \( L_{\text{BOL}} \) (10^{38} \text{ W}) | 1.24 | 1.65 | 2.24 | 1.45 |
|           | \( \sigma_v \) (km s\(^{-1}\)) | \[3000\] | \[3000\] | 3000 ± 300 | \[3000\] |
|           | Mg / Ne | \[1.2\] | \[1.2\] | 1.2 ± 0.2 | 1.2 |
|           | \( \Delta \chi^2 \) / dof | 85/2 | 136/2 | 709/4 | 255/2 |

| Abundances | C / O | \[0.13\] | \[0.13\] | 0.13 ± 0.01 | \[0.13\] |
| in the shell | N / O | \[2.41\] | \[2.41\] | 2.41 ± 0.01 | \[2.41\] |
|           | Si / O | \[0.015\] | \[0.015\] | 0.015 ± 0.005 | \[0.015\] |
|           | S / O | \[0.11\] | \[0.11\] | 0.11 ± 0.01 | \[0.11\] |
|           | Ar / O | \[0.20\] | \[0.20\] | 0.20 ± 0.01 | \[0.20\] |
|           | Ca / O (b) | \[0.01\] | \[0.01\] | < 0.01 | \[0.01\] |
|           | Fe / O | \[0.47\] | \[0.47\] | 0.47 ± 0.01 | \[0.47\] |

| Layer 1 | H Col. (10^{24} \text{ m}^{-2}) | 0.73 ± 0.02 | 2.13 ± 0.01 | 0.48 ± 0.01 | 1.22 ± 0.07 |
|         | O Col. (10^{25} \text{ m}^{-2}) | 0.44 ± 0.01 | 1.29 ± 0.01 | 0.29 ± 0.01 | 0.74 ± 0.04 |
|         | Log \( \xi \) (10^{-9} \text{ Wm}) | \[5.0\] | 4.25 ± 0.02 | \[4.9\] | 4.38 ± 0.06 |
|         | \( \sigma_v \) (km s\(^{-1}\)) | 1230 ± 20 | 225 ± 35 | 1470 ± 10 | 55 ± 20 |
|         | \( \nu \) (km s\(^{-1}\)) | −3730 ± 30 | −3360 ± 70 | −3620 ± 20 | −4560 ± 130 |
|         | \( \Delta \chi^2 \) / dof | 526/4 | 609/4 | 4083/11 | 449/4 |

| Layer 2 | H Col. (10^{28} \text{ m}^{-2}) | 2.0 ± 0.2 | 0.1 ± 0.05 | 4.15 ± 0.02 | 0.013 ± 0.002 |
|         | O Col. (10^{25} \text{ m}^{-2}) | 1.2 ± 0.1 | 0.60 ± 0.03 | 2.51 ± 0.01 | 0.008 ± 0.001 |
|         | Log \( \xi \) (10^{-9} \text{ Wm}) | 3.61 ± 0.01 | 2.50 ± 0.05 | 3.76 ± 0.01 | 2.18 ± 0.03 |
|         | \( \sigma_v \) (km s\(^{-1}\)) | 10 ± 5 | 10 ± 5 | 20 ± 5 | 160 ± 10 |
|         | \( \nu \) (km s\(^{-1}\)) | −2790 ± 20 | −3260 ± 20 | −2810 ± 10 | −3080 ± 40 |
|         | \( \Delta \chi^2 \) / dof | 526/4 | 62/4 | 2951/11 | 373/4 |

| Layer 3 | H Col. (10^{25} \text{ m}^{-2}) | 8.1 ± 0.2 | 0.5 ± 0.1 | 8.1 ± 0.2 | 2.6 ± 0.2 |
|         | O Col. (10^{22} \text{ m}^{-2}) | 4.9 ± 0.1 | 0.30 ± 0.06 | 4.9 ± 0.1 | 1.6 ± 0.1 |
|         | Log \( \xi \) (10^{-9} \text{ Wm}) | 1.40 ± 0.05 | \[< 0.01\] | 1.36 ± 0.01 | 1.18 ± 0.05 |
|         | \( \sigma_v \) (km s\(^{-1}\)) | 235 ± 10 | 70 ± 20 | 200 ± 10 | 180 ± 20 |
|         | \( \nu \) (km s\(^{-1}\)) | −3400 ± 30 | \[< 3400\] | −3340 ± 20 | −3300 ± 50 |
|         | \( \Delta \chi^2 \) / dof | 448/4 | 25/4 | 781/11 | 399/4 |

| Cold gas | Col. (10^{22} \text{ m}^{-2}) | 2.85 ± 0.01 | 2.81 ± 0.01 | 2.24 ± 0.01 | 1.97 ± 0.02 |
|          | kT (eV) | 1.13 ± 0.01 | 1.21 ± 0.01 | 1.04 ± 0.01 | 0.99 ± 0.02 |
|          | N / H | \[2.14\] | \[2.14\] | 2.14 ± 0.02 | \[2.14\] |
|          | O / H | \[2.71\] | \[2.71\] | 2.71 ± 0.01 | \[2.71\] |
|          | Fe / H | \[1.19\] | \[1.19\] | 1.19 ± 0.03 | \[1.19\] |

| Dust     | OI (10^{21} \text{ m}^{-2}) | 3.8 ± 0.1 | 6.3 ± 0.1 | 3.2 ± 0.1 | 5.3 ± 0.2 |
|          | \( \Delta \chi^2 \) / dof | 497/1 | 356/1 | 1300/1 | 948/1 |

| Statistics | \( \chi^2 \) / dof | 3538/1474 | 3980/1474 | 10380/1462 | 3390/1474 |
the Spectra A.1 and A.3, with the exception of the column of the shell with the highest ionization, 1.5 times bigger in A.1, and the column of the shell with the middle ionization, which in spectrum A.1 was 0.5 times that of A.3. Finally, the columns of the cold absorbers $X_c$ and $X_d$ both are markedly higher, by factors 1.3 and 1.2, respectively, in spectrum A.1 with respect to A.3.

The blackbody radius of spectrum A.2 is only 10000 km, and thus closer to the white dwarf surface. One might expect a higher temperature there, but the observation shows a lower temperature, ten percent lower even than the low temperature of spectrum A.1. The luminosity of the blackbody accordingly is just 10% in spectrum A.2 of that in spectrum A.1. The emission measure of the collisionally ionized plasma in spectrum A.2 is intermediate between those before in spectrum A.1 and after in spectrum A.3, at unchanged temperature. The ionization parameter of all three high-ionization absorption shells is lower in spectrum A.2. The column of the shell with the highest ionization has increased by a factor of almost three between spectrum A.1 and spectrum A.2; in contrast, the columns of the other two shells have plunged. The column of the cold absorbing gas is the same in spectrum A.2 and spectrum A.1, but the column of the dust is much higher in spectrum A.2.

The strong changes in the spectral components well within the eleven hours of the first XMM-Newton observation are striking; we will investigate these in more detail in Sects. 3.4 and 3.5.

Almost ten days later, during the second observation of V2491 Cyg with XMM-Newton, the radius of the blackbody component had shrunk to 1900 km. This remarkably low value would imply that only part of the surface of the white dwarf has this high temperature; or alternatively that the white dwarf is more massive than $1.3 M_\odot$. The luminosity of the blackbody component has declined to $L_{BB} = 3.8 \times 10^{30}$ W. The emission measure of the collisionally ionized plasma has decreased, but its temperature has increased, and as a result its luminosity now is $L_{CIE} = 1.45 \times 10^{28}$ W, to a large extent within the RGS band (see Table 3.1).

The ionization levels of the three highly ionized absorbers have dropped, as have the columns of shells 2 and 3, between Spectra A.1 or A.3 and spectrum B; the column of the highest ionization shell, shell 1, has increased. The column of the cold gas absorber has dropped by some 10%, but the column of the dust component has increased by a factor 1.7. In general, the relative changes of the parameters of spectrum B with respect to those of Spectra A.1 and A.3 are similar qualitatively, if not quantitatively, to the changes of the spectrum with the lowest countrate during the first observation, i.e. spectrum A.2.

### 3.4 Variant models

To test the robustness of some of the results from the basic models, we have fitted some variant models. The topics that we wish to investigate in particular are the nature of the hot absorption shells and the cause of the changes during the first observation.
3.4 Variant models

### Table 3.2: Absorption measure distribution.

<table>
<thead>
<tr>
<th>$\xi^b$</th>
<th>$f^{a,b,c}$</th>
<th>$\xi^b$</th>
<th>$f^{a,b,c}$</th>
<th>$\xi^b$</th>
<th>$f^{a,b,c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>$\leq 2 \times 10^{-2}$</td>
<td>2.50</td>
<td>$0.11 \pm 0.01$</td>
<td>4.50</td>
<td>$\leq 6 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.75</td>
<td>$\leq 5 \times 10^{-6}$</td>
<td>2.75</td>
<td>$\leq 1 \times 10^{-15}$</td>
<td>4.75</td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>1.00</td>
<td>$\leq 5 \times 10^{-4}$</td>
<td>3.00</td>
<td>$\leq 2 \times 10^{-2}$</td>
<td>5.00</td>
<td>$\geq 1.2$</td>
</tr>
<tr>
<td>1.25</td>
<td>$\leq 1 \times 10^{-3}$</td>
<td>3.25</td>
<td>$\leq 4 \times 10^{-8}$</td>
<td>5.25</td>
<td>$\leq 3.9$</td>
</tr>
<tr>
<td>1.50</td>
<td>$\leq 1 \times 10^{-11}$</td>
<td>3.50</td>
<td>$0.8 \pm 0.2$</td>
<td>5.50</td>
<td>$\leq 0.02$</td>
</tr>
<tr>
<td>1.75</td>
<td>$\leq 1 \times 10^{-2}$</td>
<td>3.75</td>
<td>$1.1 \pm 0.2$</td>
<td>5.75</td>
<td>$\leq 0.02$</td>
</tr>
<tr>
<td>2.00</td>
<td>$\leq 1 \times 10^{-10}$</td>
<td>4.00</td>
<td>$\leq 4 \times 10^{-4}$</td>
<td>4.25</td>
<td>$\leq 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>2.25</td>
<td>$\leq 1 \times 10^{-15}$</td>
<td>4.25</td>
<td>$\leq 1 \times 10^{-3}$</td>
<td>4.25</td>
<td>$\leq 1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$^a f = dN_H/d \log \xi$

$^b \xi$ is in units of $10^{-9}$ Wm and $N_H$ in $10^{28}$ m$^{-2}$

$^c$ The values refer to the warm model fits to spectrum A.3.

#### 3.4.1 The hot absorption shells and the bolometric luminosity

In the basic model the hot ionized absorber consists of three shells, all with the same abundances, but with distinct ionization parameters $\xi_i$. As an alternative we have fitted a continuous absorption measure distribution (AMD), using the SPEX model warm, to spectrum A.3 (see Table 3.2 and Fig. 3.6). We found that an initially continuous distribution in the course of the fitting procedure collapses to discrete components, compatible with the findings of our basic model. The model confirms the presence of at least two discrete ionization ranges with discrete velocities, represented by $\log \xi = 3.50 - 3.75$ and $\log \xi \geq 4.75$, which are consistent with what we have found with separate $x_{abs}$ components (see Table 3.1). The warm model uses the same velocity for the whole range of $\xi$, but the observed spectrum shows a relation between ionization and velocity, and this causes the warm model fit to be decidedly worse than the basic model ($\chi^2$/dof = 17300 / 1480).

We have also fitted spectrum A.3 with some models in which we fit the abundances separately for each shell; this does not improve the fits significantly.

While the limited number of absorbers suggests the presence of discrete shells with different velocities and a non-monotonous $\xi$ distribution, we note that any number of absorbers and therefore a continuous distribution is possible. The two strong peaks in the absorption measure distribution suggest the presence of two main absorbers. However, the high velocities make difficult to believe that the shells might be stable throughout the first month after the outburst and argue in favor of a continuous distribution.

The temperatures of the hot absorbing shells imply that hydrogen is fully ionized. This means that the hydrogen column of these shells is badly constrained, and for this reason we give the abundances of the various elements with respect to oxygen, fixing the hydrogen column to the proto-solar hydrogen-to-oxygen ratio in the basic model. The main effect of the presence of hydrogen is that photons that initially move from the central source in our direction are scattered into another direction. In the fully spherically symmetric case, these photons are replaced by photons moving initially in
other directions that are scattered into our direction by Thompson scattering. The slab model that we used for the absorbing shell assumes that each photon from the central source that is scattered within the shell does not reach the observer, and is not replaced by photons from initially other directions. In the presence of hydrogen, the number of electrons in the shell is much higher than in the absence of hydrogen, and a much higher number of photons is scattered. For a given observed number of photons, the slab model with hydrogen leads to a much higher number of source photons incident on the shell than the model without hydrogen.

Whether this implementation of the model is valid for V2491 Cyg is not clear. The rapid variations between spectra A.1, A.2 and A.3 may suggest that spherical symmetry does not apply. If spherical symmetry does apply, however, the number of photons should not be corrected for scattering, i.e. the luminosity of the central source will be much lower than found with the slab model. To investigate the magnitude of this effect we considered first a variant model in which we set the hydrogen content of the three shells to zero, but kept the helium. To good approximation, the electron scattering of the photons from the central source does not depend on energy within the RGS range, and thus the parameters of the fit are not affected, other than that the luminosity of the central source is reduced. In particular, the temperature of the blackbody is the same as in the basic model. Therefore we computed the luminosity for the blackbody emitter for the model in which the photon number is not corrected for electron scattering in the absorption shells by fixing all parameters to the values of the basic model, and then recomputed the luminosity of the emitter for spectrum A.3. This luminosity, at \(3.92 \times 10^{31}\)\text{W}, and with it the radius, at 3780 km, are much smaller than in the basic model.

This reasoning applies equally to a second variant model where we set the hydrogen
Table 3.3: Radii and luminosities of the central blackbody emitter. The values refer to the fits to the four spectra, for the basic model, and for variant models in which the hydrogen content, or the hydrogen and helium content of the highly ionized absorption shells are set to zero. Note that the parameters for the basic model are correct only for a highly non-symmetric case; in the spherically symmetric case the correct values for the basic model are those listed above for the no H, no He case.

<table>
<thead>
<tr>
<th></th>
<th>(R) (km)</th>
<th>(L_{BB}) ((10^{30}) W)</th>
<th>(T_{\text{eff}}) (ev)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>basic</td>
<td>no H</td>
<td>no H no He</td>
</tr>
<tr>
<td>A.1</td>
<td>21000</td>
<td>7000</td>
<td>5600</td>
</tr>
<tr>
<td>A.2</td>
<td>10000</td>
<td>4800</td>
<td>4100</td>
</tr>
<tr>
<td>A.3</td>
<td>17600</td>
<td>3780</td>
<td>2790</td>
</tr>
<tr>
<td>B</td>
<td>1900</td>
<td>1500</td>
<td>1300</td>
</tr>
</tbody>
</table>

and helium content both to zero. For spectrum A.3 the temperature again is the same as in the basic model, but the luminosity and radius drop to \(2.14 \times 10^{31}\) W and 2790 km, respectively. Table 3.3 lists the variation of the parameters with assumed hydrogen and/or helium content for the slab model, or alternatively the variation with increasing spherical symmetry.

Computing the ionization equilibria with Cloudy we assumed that the ultraviolet/optical flux is emitted by the central source. If instead it is emitted elsewhere, it may not contribute to the ionization of the shells. For this reason, we have calculated the ionization balance of the shells when the UV fluxes in the adopted SED were decreased by up to two orders of magnitude. The bolometric luminosity decreased by less than 5%, while the newly-fitted ionization parameters of the shells are systematically lower by 15–25%. The non-monotonous \(\xi\) structure as seen in Fig. 3.6 is still preserved and the other main physical parameters such as column densities and abundances are consistent within the errors. The overall scenario thus is unaffected.

3.4.2 The changes between Spectra A.2 and A.3

The dramatic changes in brightness of the X-ray source during the first observation with XMM-Newton are explained in the basic model by a drop in the luminosity of the central blackbody emitter, combined with changes in the column of the ionized absorption shells. The luminosity drop of the central source is the result of a smaller radius and a lower temperature (see Table 3.3). In the variant models discussed in the previous section, where the hydrogen and helium contents of the absorption shells are set to zero, the drop in luminosity between A.3 and A.2 is much less pronounced, since in these models the lower temperature of spectrum A.2 is partially offset by a larger radius (Table 3.3). It is remarkable that \(R\) in the models with reduced hydrogen and helium contents drops monotonically with time; in the basic model \(R\) increases between spectrum A.2 and spectrum A.3.

To investigate whether it is possible to describe the change between spectra A.2 and A.3 with a change in the blackbody and collisionally ionized emitters only, we fitted...
spectrum A.2 with an alternative model, in which all parameters related to the absorption components were fixed to the values for spectrum A.3, and only the parameters for the blackbody and for the collisionally ionized plasma were allowed to change. The resulting fit is significantly worse ($\chi^2 \approx 5000$, as compared to the best basic fit $\chi^2 \approx 4000$). The $\chi^2$ for this fit is dominated by the bad fit to the emission between 25-29 Å, and around 16 Å.

To investigate whether the lower luminosity may be explained by increased absorption due to increased columns of the ionized shells only, we fit spectrum A.2 with a model in which the parameters for the central emitters are fixed to the best values of the basic model for spectrum A.3, and only the columns and ionization parameters of the shells were allowed to vary. The best fit with this variant model has $\chi^2 \approx 5500$, significantly worse than the basic fit for spectrum A.2.

To investigate whether the lower luminosity may be explained by increased absorption due to an increased column of the neutral gas and/or an increased column of the dust, we fit spectrum A.2 with a model in which the columns of the neutral gas and of the dust are fitted, but all other parameters were fixed to the best-fit parameters of the basic model for spectrum A.3. This gives a poor fit, with $\chi^2 \approx 8000$. A model in which the central emitter is only partially absorbed by an increased neutral hydrogen column does not fit the spectrum at all, because the HI absorption is strongest at $\lambda \gtrsim 24$ Å, a part of the spectrum that remains relatively bright. Therefore, we can exclude absorption by cold clumpy material.

Finally, we have checked whether an addition of a radiative recombination continuum (RRC) to the model of spectrum A.2 improves the fit. The presence of this emission is suggested by emission features near 16.8 Å and 18.4 Å. We take into account the recombination of the most relevant ions of took, nitrogen and oxygen. The addition of RRC to the model does not lead to a significant improvement of the fit.

### 3.4.3 Derived mass loss rates and model consistency

Our fits to the spectra imply a mass loss rate

$$\dot{M}_w = \left( \frac{\Omega}{4\pi} \right) 4\pi r^2 \mu m_H f_c n_H v = \left( \frac{\Omega}{4\pi} \right) 4\pi \mu m_H v \frac{L}{\xi},$$

(3.2)

where $\mu$ is the mean atomic weight in units of the hydrogen mass $m_H$, $f_c$ is a factor allowing for clumpiness of the density distribution ($f_c \leq 1$), and where $\Omega = 4\pi$ in the case of spherical symmetry. The observed spectrum gives $\xi$ and $v$ for each shell, almost independent of $L$. With the parameters of the standard model fit to spectrum A.3, we obtained the mass loss rates listed in Table 3.4. Note that these values are valid for one time interval only – i.e. the time of maximum X-ray flux, and thus may overestimate the outflow-rate averaged over the outburst. From Eq. 3.2 we note in addition that the derived value of $\dot{M}_w$ scales with the luminosity $L$ of the central source, and thus will be smaller when the layers are hydrogen- and/or helium-poor (see Table 3), and also when the layers are spherically symmetric, in which case the xabs model overestimates the central luminosity.
Table 3.4: Derived mass loss rates and shell parameters. The parameters listed are valid for the standard model for spectrum A3. If the layers are depleted in hydrogen and/or helium, the actual mass loss rate would be lower.

<table>
<thead>
<tr>
<th></th>
<th>layer 1</th>
<th>layer 2</th>
<th>layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{M}/(f_c \Omega \mu)(M_\odot/\text{yr})$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$4.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$r/(f_c \beta r_{BB})$</td>
<td>127</td>
<td>202</td>
<td>2.6$\times 10^7$</td>
</tr>
<tr>
<td>$n_H \times (f_c \beta)^2$</td>
<td>$2.2 \times 10^{18}$</td>
<td>$1.2 \times 10^{19}$</td>
<td>$1.8 \times 10^{11}$</td>
</tr>
</tbody>
</table>

The depths of the absorption lines, combined with the fitted abundances, are converted to the hydrogen column density $N_H \equiv \int n_H dr \approx f_c n_H \Delta r$ where $\Delta R$ is a typical length scale. Our model implies that this length scale is shorter than the distance to the central source, $\Delta r \equiv \beta r < r$, and this may be used to obtain an upper limit to the distance $r$:

$$L/\xi N_H = \frac{n_H r^2}{f_c n_H \beta r} \Rightarrow r = f_c \beta \frac{L/\xi}{N_H} \quad (f_c, \beta < 1),$$

(3.3)

and from this a lower limit to the density

$$n_H = \frac{L}{\xi r^2} = \frac{\xi}{L} \left(\frac{N_H}{f_c \beta}\right)^2.$$  

(3.4)

Note that the definition and computation of $\xi$ involves the physical density (i.e. not the space-averaged density), and therefore does not contain the clumpiness factor $f_c$. The mean atomic weight $\mu$ is 1.42 for proto-solar H-He abundances and 3.58 for H-He abundances decreased by two orders of magnitude. Another interesting parameter is the time scale at which the gas in the outflow adjusts its ionization balance. This may be calculated from the ionization balance and $\xi$-values of the fits. Through the SPEX tool rec_time we determined the O VIII recombination times for layers 1 and 2. They spread between a few (H-He rich slabs) to up to ten (H-He poor slabs) seconds, which means that the gas is responding instantaneously to the variations of the photo-ionizing continuum of the source and that the observed features are linked to the variability of the source.

### 3.5 Discussion

From our fits it is clear that the central blackbody emission varies rapidly during our first observation on a time scale of hours. The variations are likely exaggerated by the slab model: in full spherical symmetry, and also in the absence of hydrogen and helium in the ionized absorption shells, the changes are still significant, but much less so. Forty days into the nova outburst, we may well be looking at shells whose abundances are affected by nuclear reactions. Indeed, the abundances that we derive for carbon, nitrogen and oxygen indicate that this is the case. This implies that the hydrogen and helium abundances of absorption shells are much lower than solar, in comparison to
the elements just mentioned. Even in the absence of spherical symmetry, therefore, the variation of the central source is less pronounced than implied by our basic model, and probably agrees better with the numbers found for the models in which the absorption shells contain no hydrogen and/or helium.

The response time required for the ionization equilibrium of shells to respond to changes in the ionizing continuum is a few seconds, which means that the photo-ionization balance of the shells responds almost instantaneously to variations in the source flux and that its luminosity might indeed have changed. The mass loss rate in our standard model for spectrum A.3 for the third shell in particular is rather high compared to the common limits $10^{-4} - 10^{-3} M_\odot/yr$ found for other novae (Kovetz et al. 1987; Kato & Hachisu 1989; Smith & Owocki 2006). The derived mass loss rates for all three layers are lower in the models with reduced hydrogen and/or helium content of the absorbing shells.

As discussed in Section 4.1, the blueshifted absorption lines are caused by photons from the central source that initially move in our direction and are scattered into another direction. If the dimension of the shell is large with respect to the size of the white dwarf, and if the optical depth of the shell in the lines is not too high, this will lead to a P Cygni profile, because we see photons initially moving in other directions and then scattered into our direction in emission, both blue- and red-shifted. The emission and absorption should have equal strength. In the spectrum of V2491 Cyg this is clearly not the case. One explanation is that the shell is not large with respect to the white dwarf, so that a large part of the receding half is occulted. Similarly, a high optical depth in the shell may cause photons scattered from the receding half of the shell to be reabsorbed before escaping in our direction. And finally, a large asymmetry in the shell may also reduce the strength of the redshifted emission.

Carbon and sulfur are about an order of magnitude less abundant than nitrogen and oxygen, and elements such as silicon, argon and calcium are much less abundant. This suggests that the white dwarf in V2491 Cyg is an O-Ne and not a C-O white dwarf. The strength of the Ne IX-X lines as compared to the C V-VI lines supports this conclusion, as do observations in other wavelength regions (Lynch et al. 2008; Helton et al. 2008; Naik et al. 2009; Munari et al. 2011).

The strongest feature in all X-ray spectra is the rest frame O I K-edge around 23.0 Å, which is well reproduced in the fits together with the corresponding O I 1s-2p absorption line at 23.5 Å. Other features of the cold CSM/ISM are the Fe I L-edge around 17.5 Å and the N I 1-2p absorption line at 31.2 Å, both well fitted by our models. Neutral oxygen and nitrogen are highly overabundant, whereas iron is slightly overabundant, with respect to solar abundances. This suggests that part of the cold absorption originates in enriched circumstellar matter close to V2491 Cyg. The reduction of the column and the decrease in temperature of the cold absorber between spectra A.1 and B suggests that the CSM column is mostly derived from the current nova outburst, and still expanding, albeit slowly. Page et al. (2010a) suggested that the reduction of the column stops at $2.2 \times 10^{25} \text{ m}^{-2}$ some time after our second observation. This final value then corresponds to the interstellar component. If the total O I column is equally divided between CSM and ISM, the ISM may have a near-solar abundance for oxygen, and sub-solar abundance for iron, implying that iron is depleted by dust.
3.6 Conclusions and prospects

The optical flux defines the nova outburst, and thus clearly must come from the expanding nova envelope; the ultraviolet flux changes in tandem with the optical flux, and therefore also originates from the nova envelope. As can be seen from Fig. 3.5, our model fails to predict the correct level of the ultraviolet and optical fluxes by several orders of magnitude. This indicates that our model applies only, if at all, to the X-ray part of the spectrum, which must originate from a very different layer in the expanding envelope, presumably much closer to the white dwarf than the layers responsible for the optical/ultraviolet spectrum. This conclusion is confirmed by the observation that the marked changes in the X-ray flux during the first XMM-Newton observation are not accompanied by changes in the optical and/or ultraviolet fluxes.

Because the absorption lines from the shells are shifted from the rest wavelengths by the high outflow velocities, and because hot atmospheres do not show deep absorption lines even at the rest wavelengths using a blackbody spectrum as the central source is not as poor choice as might appear at first sight. As a first test we have tried a model atmosphere spectrum that replaces the blackbody as the central source. Following Ness et al. (2011) we used the best fitting TMAP model of Rauch & Werner (2010) (007, with $\log g = 9$ and $T = 10^6$ K). This provides an even worse fit with $\chi^2 = 15$ with three shells, 18 with two shells, 32 with just one shell and 59 without any photo-ionized absorber (instead of 7 from the BB fit) because O\text{VIII} / N\text{VII} line ratio (the most important in the spectrum) cannot be reproduced by the atmosphere model. It may be necessary to consider models with different abundances and outflows which, however, are currently not available and we therefore refrain from a systematic parameter study of the atmosphere model parameters.

3.6 Conclusions and prospects

Our spectral analysis of nova V2491 Cyg suggests that the absorption by highly-ionized ions is caused by non-monotonous, possibly discrete, ejecta shells with different outflow velocities and ionization levels. Variations on time scales of hours occur both in the luminosity of the central source and in the ionization level and columns of the absorption shells. We find that in our scenario of photo-ionization equilibrium the expanding gas is responding almost instantaneously to the variations in the source ionizing continuum. Our upper limits for the mass loss rate of each shell agree with those estimated for other novae, especially if the shells are depleted in hydrogen.

The values derived from the fits for the luminosity and radius of the central source depend on the nature of the models that are applied, and therefore must be considered uncertain. In the spherically symmetric case, however, the radius of the central emitter of X-rays decreases monotonically with time, and therefore must be in the increasingly transparent expanding nova envelope. The values derived for the abundances in the ionized absorption shells do not depend on the details of the models, and therefore may be considered more secure. These abundances indicate that the white dwarf in V2491 Cyg is an O-Ne white dwarf.

Improvements to our pilot models can be made in several ways. First, it would be useful to replace the central blackbody emitter with an appropriate white-dwarf at-
mosphere model. We have tested a model in which the TMAP model substitutes the blackbody, but is still absorbed by the three shells. However, this model provides even poorer results than those obtained with our standard fits with a blackbody continuum. In the future atmosphere models must take into account different abundances and outflows.

Second, it will be necessary to iterate between the computation of the ionization structure of the ionizing shells for a given spectral energy distribution, and the computation of the spectral energy distribution and elemental abundances from the fit, for each of the four observed spectra separately. For this improvement it is also necessary to determine the distance more reliably: a close distance implies a lower luminosity and thereby a lower ionization parameter of the shells. Finally, it would be useful to obtain constraints on the hydrogen contents of the hot ionized absorption shells, perhaps from ultraviolet observations. Ultraviolet observations may also help in determining the location of origin of the optical/ultraviolet flux.

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Multiwavelength campaign on Mrk 509
IX. The Galactic foreground

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Abstract

The diffuse gas in and nearby the Milky Way plays an important role in the evolution of the entire Galaxy. It has a complex structure characterized by neutral, weakly and highly ionized gas, dust, and molecules. We probe this gas through the observation of its absorption lines in the high-energy spectra of background sources. We
use high-quality spectra of AGN Mrk 509, located at high Galactic latitudes obtained with XMM-Newton, HST and FUSE. We use advanced absorption models consisting of photo- and collisional-ionization. We constrain the column density ratios of the different phases of the interstellar medium (ISM) and measure the abundances of C, N, O, Ne, Mg, Al, Si, S, and Fe. We detect seven discrete interstellar clouds with different velocities. One is a typical low-velocity cloud (LVC) and three belong to the family of the intermediate-velocity clouds (IVCs) found near the Galactic disk. These four clouds show large deviation from Solar abundances in the gas phase, mostly caused by dust depletion. The other three clouds are ionized high-velocity clouds (HVCs) and are located either in the Galactic environment or in the Local Group halo as suggested by the signatures of collisional ionization. The similar abundances and ionization structure of the HVCs suggest a common location and origin: they might belong to the remainder of an extragalactic cloud which was captured by the Galaxy. We have shown that combined UV / X-ray spectroscopy is a powerful tool to investigate the ISM. In common Galactic clouds, like LVCs and IVCs, the ISM shows a complex structure consisting of at least three different temperature phases.

4.1 Introduction

The interstellar medium (ISM) drives the evolution of the Galaxy: it is enriched with heavy elements during the course of stellar evolution, and it also provides the source of material for the subsequent star formation. In the spectra of background sources the ISM gives rise to reddening and absorption lines. The ISM shows a clear multi-phase structure (for a review, see Ferrière 2001). The cold phase is a blend of dust, molecules and gas below $10^4$ K. The warm ionized gas is weakly ionized, with a temperature of $\sim 10^4$ K. The hot ionized gas is characterized by temperatures of about $10^5$ K.

The multi-phase medium plays an important role in the evolution of the Galaxy. One of the parameters that affect the stellar evolution is the metallicity of the star forming regions. Stellar winds and supernovae expel part of the interstellar gas out of the Galactic disk, but gravity generally stops the gas from escaping, such that it falls back through the process known as “Galactic fountain” (Shapiro & Field 1976). Gas accreted from smaller galaxies, e.g. the Magellanic Clouds, and the intergalactic medium increases the reservoir of low metallicity gas. High-velocity clouds (HVCs) play a crucial role in this process.

HVCs contain neutral hydrogen at velocities incompatible with a simple model of differential Galactic rotation. In practice one uses a Local Standard of Rest velocity $V_{\text{LSR}} \geq 90 \text{ km s}^{-1}$ to define HVCs (for a review see Wakker & van Woerden 1997). ISM absorbers with $30 \lesssim V_{\text{LSR}} \lesssim 90 \text{ km s}^{-1}$ are usually defined as intermediate-velocity clouds (IVCs). Both IVCs and HVCs might originate from our Galaxy or have an external origin. They could be debris from Galactic fountains or infalling Local Group gas (Blitz et al. 1999). Of course, a Galactic fountain origin would imply metallicities near solar, while infall from the Local Group or the intergalactic medium (IGM) would imply metal poor gas. The presence of infalling matter is required in order to maintain star formation in the Galaxy: without a substantial replenishing of the gas available...
the star formation would stop in a period much shorter than the Hubble Time. HVCs are thought to contain enough mass to sustain star formation rate (SFR) in the Galaxy (Lehner & Howk 2011).

A multiwavelength approach provides the means to analyze the ISM in a complete way. For instance, combined UV and X-ray spectroscopy provides accurate column densities and the velocity structure of the most abundant ionic species. Ionic species like Si II-IV, C II-IV, N V and O VI especially, are quite common in HVCs (Sembach et al. 2003). In the last decade interstellar absorption lines in UV spectra of background stars have provided the distances of several IVCs and HVCs (see e.g. Richter 2006; Lehner & Howk 2011, and references therein). In summary, all the main H I complexes are known to be Galactic. IVCs are at typical distances of \( \lesssim 2 \) kpc, while HVCs with \( 90 \lesssim V_{\text{LSR}} \lesssim 170 \) km s\(^{-1}\) are found between 4–13 kpc. No cloud is found at \( V_{\text{LSR}} \geq 170 \) km s\(^{-1}\) towards halo stars, while several of them are found towards AGNs, which suggests that these very-high velocity clouds (VHVCs) are at larger distances. However all are thought to be within 40 kpc (Richter 2006), except the Magellanic Stream which is at about 50 kpc, much closer than the typical distances in the Local Group halo. A plausible scenario is that VHVCs are the next generation of HVCs infalling towards the Galactic disk and slowing down during their interaction with it (Lehner & Howk 2011).

The AGN Mrk 509 has been intensively studied for both its intrinsic spectral features and its interesting line-of-sight. The Galactic latitude for Mrk 509 is –30 degrees and crosses the halo of our Galaxy, resulting in an important contribution of ionized gas. First evidence for ionized gas was found by York et al. (1982), who discovered significant absorption from Si II, Fe II and C IV in the spectra taken with the IUE satellite. They also observed strong Ly\( \alpha \) absorption as well as red-shifted lines from Ca II and Na II in optical spectra. Blades & Morton (1983) attributed these shifted lines to corotating gas in our halo. This was confirmed by the detection of neutral hydrogen with \( V_{\text{LSR}} \sim 60 \) km s\(^{-1}\) (McGee & Newton 1986). Sembach et al. (1995) and Sembach et al. (1999) discovered two sets of lines of Si III-IV and C IV with large velocities, i.e. \( V_{\text{LSR}} \sim -230 \) km s\(^{-1}\) and \(-280 \) km s\(^{-1}\), which were attributed to absorption by HVCs. Sembach et al. (2003) argued that these clouds are photo-ionized by the extra-Galactic background, but the presence in large quantities of hot gas such as O VI cannot be explained by the photo-ionization models and suggests that these clouds are probably interacting with the hot Galactic corona or the Local Group medium. To explain the ionized C, Si and O column densities Collins et al. (2004) concluded that the HVCs have multiple phases. They showed that the Si III-IV and C IV can be produced by a QSO photo-ionizing background, while the O VI indicates collisional ionization due to the interaction with the Galactic corona. We note that the presence of molecular H\(_2\) in the LOS (Wakker 2006) affects the spectral region near the O VI UV line and its column density estimate.

More than fifteen years after the discovery of these HVCs, their structure is not yet well understood. To solve these questions improved collisional and photo-ionization models are needed to constrain the ionization processes occurring in HVCs, as well as a multiwavelength approach which uses all the available archival data in order to increase the number of ions detected as well as the ionization parameter range that we can sample, and to disentangle the molecular H\(_2\) and the O VI absorption.
This article is one of a series of papers analyzing the deep and broad multiwavelength campaign on Mrk 509. The overview of the campaign is presented in Kaastra et al. (2011b), hereafter paper I. Here we present the analysis of the interstellar clouds in the LOS towards Mrk 509 through a combined UV / X-ray analysis of the spectra taken with the Hubble Space Telescope / Cosmic Origin Spectrograph (HST/COS) (Green et al. 2012) and the XMM-Newton Reflection Grating Spectrometer (RGS, den Herder et al. 2001). Our analysis is focused on both the LVC, IVCs and HVCs and the dust present along the LOS towards Mrk 509. We constrain velocity, ionization and chemical structure of the ISM for the different ionic species.

The paper is organized as follows. In Sect. 5.2 we present the data. In Sect. 5.3 we report the relevant spectral features that we analyze. In Sect. 5.4 we describe the models we use and the results of our analysis. The discussion and the comparison with previous work are given in Sect. 5.5. Conclusions are reported in Sect. 5.6.

4.2 The data

As part of our multiwavelength campaign we observed Mrk 509 in the far-ultraviolet wavelength band between 1155 Å and 1760 Å using the Far-Ultraviolet Channel and the medium resolution gratings of the Cosmic Origins Spectrograph (COS) onboard the Hubble Space Telescope (HST). A detailed explanation of the observing strategy, instrument performance, data reduction, and calibration can be found in Kriss et al. (2011), hereafter paper VI. They also present a full-scale plot of the high-resolution spectrum.

To summarize the data briefly, the observations were taken on 2009 December 10 and 11 simultaneously with the Chandra LETGS observations in our campaign (Ebrero et al. 2011). Using the COS gratings G130M and G160M, we obtained total exposure times of 9470 s and 16452 s, respectively. With each grating, we used only two different grating tilts with a single FP-POS for each to avoid creating gaps in the spectral regions of interest including the AGN outflow features. The data were processed with the COS calibration pipeline v2.11b at STScI. With central wavelengths of 1309 and 1327 for G130M, 1577 and 1589 for G160M, and two exposures at each tilt, we obtained a sufficient variety of independent placements of the spectrum on the detector to identify instrumental features in our high signal-to-noise spectrum. Known features such as dead spots were excluded from the combined data; correctable features such as grid-wire shadows were removed via a customized flat-field treatment described by Kriss et al. (2011). Kriss et al. (2011) also describe improved wavelength calibration applied to the data. Finally, they deconvolved the spectra using a Lucy-Richardson algorithm to remove the effects of the broad wings of the COS line-spread function (Ghavamian et al. 2009; Kriss 2011). This correction is essential to recover the true depths of narrow interstellar absorption lines; comparison to prior STIS spectra of Mrk 509 validates the effectiveness of the deconvolution. We use the original spectrum to identify weak spectral features, while we use the deconvolved spectrum for measuring the depth and width of identified absorption lines.

For the X-ray portion of our study we use the stacked XMM-Newton RGS spectrum
of Mrk 509 that consists of ten ~60 ks individual observations. The observations and data reduction for this stacked RGS spectrum are described by Kaastra et al. (2011a), hereafter paper II. Briefly, they used the SAS 9.0 software package to reduce the ten individual observations. They then created a fluxed spectrum for each observation and stacked these, using RGS 1 and 2 and both spectral orders, and taking the effects of the XMM-Newton multi-pointing mode into account.

In addition to the COS and RGS spectra, we also use an archival spectrum obtained with the Far Ultraviolet Spectroscopic Explorer (FUSE) for the O\textit{VI} 1032 Å absorption line. The FUSE data are described in paper VI.

For our spectral analysis we use SPEX\textsuperscript{1} version 2.03.00 (Kaastra et al. 1996). SPEX is a software package optimized for the analysis and interpretation of high-resolution UV and X-ray spectra. In SPEX one can simultaneously use different components for continuum emission as well as absorption by photo-ionized or collisionally-ionized gas (see the SPEX manual). We scale elemental abundances to the proto-Solar values recently recommended by Lodders & Palme (2009). We use a linear scale for the abundances. Throughout this paper we use SI units which are also the units system used in our spectral codes, adopt $1\sigma$ errors, and use $\chi^2$ statistics unless otherwise stated. We define high-ionization ions to be more than four times ionized, like O\textit{VI-VIII}, while single to four times ionized ions are defined as low / intermediate-ionization ions, as commonly done in X-ray spectroscopy.

### 4.3 Spectral features

#### 4.3.1 The COS spectrum

Most features in the COS spectrum are foreground absorption lines due to the ISM of the Galaxy. We detected absorption lines from seven discrete ISM components (see Table 7, paper VI). We also found three absorption lines due to the diffuse intergalactic medium in the LOS towards the AGN. In Figs. 4.1, 4.2 and 4.3 we plot the prominent interstellar lines present in the COS spectrum. The lines are sorted according to their ionization state and ionization potential. All lines are plotted in velocity space and in units of normalized flux. The zero-velocity of the scale is given by the laboratory wavelength of each transition. For consistency and easy comparison with previous work we then convert velocities to the Local Standard of Rest (LSR). The conversion from the laboratory to the LSR scale is given by $v_{\text{LSR}} = v_{\text{Lab}} + 11.16 \text{ km s}^{-1}$ (Blades & Morton 1983).

In the COS spectrum the ISM features are resonance lines and encompass up to 5 ionization states, e.g. from N\textit{I} to N\textit{V}. The strongest lines are the N\textit{I} triplet around 1200 Å, the O\textit{I} line at 1302 Å, and the Fe\textit{II} and Al\textit{II} lines at 1608.4 and 1670.8 Å, respectively. Multiple strong transitions from both Si\textit{II} and S\textit{II} are shown, as well as C\textit{IV} and Si\textit{IV} doublets. The C\textit{II} and Si\textit{III} lines are heavily saturated. We confirm the presence of several discrete absorbers, seven in the case of C\textit{IV} as found in paper VI,

\textsuperscript{1}www.sron.nl/spex
Figure 4.1: HST/COS absorption lines from the cold phase (ionization states I-II). The flux is normalized to the continuum emission and the lines are displayed in the Local Standard of Rest system. The rest frame wavelength of each resonance line is also given. The dotted lines represent the average velocities of the seven cloud systems (Kriss et al. 2011), which are also labeled as A to G.

with $v_{\text{LSR}}$ of about -295, -240, -125, -65, +5, +65 and +90 to +130 km s$^{-1}$. We label these absorbers with alphabetical letters ranging from A to G and sort them according to their $v_{\text{LSR}}$ (Table 4.1). Moreover, we adopt the standard nomenclature for the clouds: the absorbers that produce components A, B and C are HVCs as their velocity modulus is greater than 100 km s$^{-1}$. The absorbers responsible for components D, F, and G are intermediate velocity clouds (IVC). Component E is a low-velocity cloud (LVC).

4.3.2 The FUSE spectrum

FUSE observed Mrk 509 in 1999 for about 52 ks (Kriss et al. 2000) and in 2000 for 62.1 ks (paper VI). We use only the last observation because of its higher S/N ratio. We use the FUSE spectrum mostly for the analysis of the absorption lines due to the interstellar O VI (see Fig. 4.5).
Figure 4.2: HST/COS absorption lines from the cold phase (continued). Units are same as in Fig. 4.1.
Figure 4.3: HST/COS absorption lines from the warm phase (ionization states III-V). Units are same as in Fig. 4.1.
4.3.3 The RGS spectrum

The XMM-Newton RGS spectrum of Mrk 509 is complex because most of the observed features are intrinsic to the AGN and some of them blend with foreground absorption lines as shown in paper II. Absorption and emission lines intrinsic to the AGN can be distinguished from the ISM lines as the former are significantly red-shifted. For a complete analysis of the AGN intrinsic absorption we refer to Detmers et al. (2011), hereafter paper III. The strongest ISM features are the O I and N I absorption lines at 23.5 Å and 31.3 Å, respectively. Clear evidence of highly ionized gas is provided by the O VII-VIII lines at 21.6 and 19.0 Å. We plot the individual RGS absorption edges of neutral O, Fe, and N together with the most prominent high-ionization lines in Fig. 4.7.

4.4 Spectral modeling of the ISM

Our analysis focuses on the absorption lines of the ISM along the LOS towards Mrk 509. These lines are narrower than the features intrinsic to the AGN and always narrower than 1 Å. The only exception is the H I Lyα absorption line at 1215.67 Å, which has a FWHM of 20 Å (see Fig. 4.4). In order to reproduce both the AGN continuum and narrow and broad emission lines, we use the continuum emission model of paper VI. The spectral ranges that are strongly affected by intrinsic absorption were excluded as the AGN analysis is carried in other paper (Kriss et al. 2011). For the RGS spectral modeling we used the continuum plus line emission model (Model 2) given in paper III for the warm absorber. First we analyze the ISM in the UV and in the X-rays separately due to the different resolution of the instruments. The different velocity components are resolved in the UV spectra (see Fig. 4.1, 4.2 and 4.3), but this is not yet possible in the X-ray band.

4.4.1 UV spectral fits

We have performed the UV analysis in two steps. First, we use an empirical model to estimate the velocity shift and dispersion of each absorption line and the ionic column density. This model provides information on the significance and kinematics of all the components. It further gives hints of their ionization state and location within the Galaxy. In the second method we use physical models to provide a more realistic description of the several foreground absorbers. These models provide important information on the ionization state, abundances and the sources responsible for heating the ISM. A final simultaneous fit to the UV and X-ray spectra was performed to obtain robust results by covering the entire range of ionization states.

An empirical slab model for the COS–UV spectra

The first ISM model we use consists of seven slab components, which are required in order to reproduce the 7 different kinematic ISM absorbers observed in the COS and FUSE spectra. Only C IV clearly shows all seven components (see Fig. 4.3). Excluding
C II, the low-ionization absorption lines require no more than four components. Thus low-ionization gas is not detected for the HVCs. The slab model in SPEX calculates the transmission of a slab of material, where all ionic column densities can be chosen independently. This has the advantage that the spectrum can be fitted without any prior knowledge of the ionization balance. The slab model jointly fits all the lines that are produced by the same ion. After an acceptable spectral fit is obtained, we can compare the observed column densities with those predicted from photo-ionization models. Free parameters in the slab model are the velocity dispersion $\sigma_v$, the Doppler velocity shift $v$ and the ionic column density $N$.

For some UV saturated lines there is a degeneracy between the velocity dispersion and column density, hence the determined column density is uncertain. For several ions we only detect saturated lines in the UV spectrum, thus we have performed simultaneous fits for lines with similar ionization potential, like H I, N I and Mg II (see Fig. 4.4), tying their $v$ and $\sigma_v$. All lines of the same ion were simultaneously fitted like the four C I lines (see Fig. 4.1), the five Si II and three S II lines (see Fig. 4.2), as well as the Si IV, C IV and N V doublets (see Fig. 4.3). In order to simplify our model and to shorten the CPU time we force the component A, B and C (HVCs) to have the same velocity dispersion, and similarly for components E, F and G (IVCs, see Table 4.1). A preliminary fit to the strong, resolved lines of N I, Fe II, S II, C IV and S IV did give consistent values for the velocity dispersion $\sigma_v$ within these groups. Only component D shows a rather smaller $\sigma_v$, thus we treat it separately. In the cases where component D was too weak or blended, we froze $\sigma_v$ to the value obtained for O I, the strongest line in component D. The N V 1238.8 Å line is affected by IGM absorption (paper VI) and the O VI HVC lines are affected by the presence of molecular H$_2$ (Wakker 2006). To reproduce the IGM line we added a slab of H I with $v = 5700$ km s$^{-1}$, $\sigma_v = 40$ km s$^{-1}$ and very small column density $\log N_{\text{HI}} = 17.2$ m$^{-2}$ in agreement with paper VI. Two Gaussians were added to model the H$_2$ absorption at 1031.2 Å. These Gaussians have velocity shifts of +3 and +60 km s$^{-1}$, $\sigma_v = 8$ km s$^{-1}$, and equivalent widths of 0.06 and 0.03 Å, respectively in agreement with Wakker (2006). Thus, both the N V and O VI column densities, as given in Table 4.1, are corrected by IGM and H$_2$ contamination. The C II absorption lines appear to be different from the other low-ionization ions like S II and Si II. Among the low ions, only C II clearly shows high-velocity absorption. Moreover, a separate fit of the C II and C I absorption lines provides a column density ratio C II/C I $\sim 100$ and a velocity dispersion ratio $\sigma_{\text{C II}}/\sigma_{\text{C I}} > 3$, which are inconsistent with the other column density ratios of low ions like O I-II and N I-II. This suggests that the bulk of the neutral carbon in the cold phase is depleted into dust grains and that most of the C II is provided by the warm phase as confirmed by our physical models (see Sect. 4.4.2.) For these reasons we prefer to fit the C II absorption lines together with the intermediate ions. We empirically model the H I absorption assuming that it is all in the cold phase. Our physical model confirms that the neutral hydrogen present in the cold phase is indeed two orders of magnitude larger than that in the warm and hot phases.

In Figs. 4.4 and 4.5 we show the data and best fit models for the most prominent lines of the cold, warm and hot ISM phases. The results of the best fit with the seven slab components are reported in Table 4.1. They are sorted according to the velocity shift.
(columns) and ionization potential (rows). We also group the ions which have been fitted together: H I, N I and Mg II; Si II and Al II; Fe II and Ni II; C II-IV, Si III-IV and N V. We generally detect low-ionization lines only for the LVC and IVCs (components E and D, F and G), thus four slab components are sufficient to model these low-intermediate velocity absorbers. However, we need seven slab components for modeling the mildly ionized gas providing the bulk of C II and all two or more times ionized ions. We note that the $\sigma_v$ on average increases with the ionization state. A comparison of the column densities of the three HVCs (component A to C) shows that the fastest component A is the least ionized.

In order to simultaneously fit the absorption lines of the mildly ionized gas, we applied a few wavelength shifts to certain ions to match both the IVC and HVC features. These shifts are likely due to residual errors in the COS and FUSE wavelength calibration. We applied no shift for both C IV and Si IV as their profiles perfectly match (see Fig. 4.5). The Si III lines have been shifted by $-8\, \text{km\, s}^{-1}$, the C II and N V lines by $-10\, \text{km\, s}^{-1}$. We also shifted the FUSE O VI lines by $-14.5\, \text{km\, s}^{-1}$ to obtain a match with the COS C IV HVC lines. Because the O VI features are blended and affected by H$_2$ absorption, in the spectral fits we prefer to fix all the O VI LOS velocities to those of the C IV and S II lines, which are well constrained.

A physical analysis of the interstellar absorbers requires more realistic models. In the next subsection we test two different SPEX models to reproduce both the neutral and ionized gas phases: the hot and the $xabs$ models, which reproduce collisional and photo-ionization respectively.

**A collisionally-ionized model for the cold gas**

The hot model in SPEX calculates the transmission of a collisionally-ionized equilibrium (CIE) plasma. For a given temperature and set of abundances, the model calculates the ionization balance and then determines all the ionic column densities by scaling to the prescribed total hydrogen column density. At low temperatures this model mimics the neutral interstellar gas (see SPEX manual and Kaastra et al. 2009). Free parameters in the hot model are the hydrogen column density $N_H$, the temperature $T$, the velocity dispersion $\sigma_v$ and shift $v$ and the abundances.

Following the ISM analysis of Pinto et al. (2010), we have first modeled the cold gas with a low-temperature collisionally-ionized gas. The interstellar cold gas is responsible for the low ionization absorption lines: H I, C I, N I, O I, Mg II, Al II, Si II, S II, Ni II, and Fe II. These lines arise from the LVC and IVCs (components D-G) and no significant low-ionization absorption is detected at high outflow velocities (see Table 4.1). Thus, we modeled the cold gas with just four CIE components, one for the LVC and three for the IVCs. As previously assumed for the slab model, we take the same $\sigma_v$ for the three reddest absorbers, E-F-G. We also adopted the same abundances for components D to G: the poor statistics and the line blending give degenerate fits that do not allow us to constrain the abundances of these four absorbers separately. For the strongest components E and F we performed a fit with decoupled abundances for S, Fe and N. The abundances of both components were consistent within the errors.

At first we assumed proto-Solar abundances. The fit was not satisfactory for any
Table 4.1: Spectral fits to the COS and FUSE spectra using the empirical model with 7 slab components. Dashes are non detections.

<table>
<thead>
<tr>
<th></th>
<th>A (a)</th>
<th>B (a)</th>
<th>C (a)</th>
<th>D (a)</th>
<th>E (a)</th>
<th>F (a)</th>
<th>G (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>( \approx 2.0 ) (c)</td>
<td>4.5 ( \pm 0.4 )</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(-50 \pm 10)</td>
<td>(-1 \pm 1)</td>
<td>62 ( \pm 1)</td>
<td>100 ( \pm 10)</td>
</tr>
<tr>
<td>C I (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>15.7 ( \pm 0.3)</td>
<td>17.6 ( \pm 0.1)</td>
<td>16.8 ( \pm 0.1)</td>
<td>16.2 ( \pm 0.1)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>&lt; 10 (d)</td>
<td>—</td>
<td>—</td>
<td>2.0 ( \pm 0.4)</td>
<td>—</td>
<td>9 ( \pm 1)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
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<td>—</td>
<td>—</td>
<td>(-64 \pm 1)</td>
<td>(+7 \pm 3)</td>
<td>71 ( \pm 5)</td>
<td>131 ( \pm 10)</td>
</tr>
<tr>
<td>O I (c)</td>
<td>&gt; 16.4 (d)</td>
<td>—</td>
<td>—</td>
<td>19.2 ( \pm 0.4)</td>
<td>21.1 ( \pm 0.2)</td>
<td>20.7 ( \pm 0.1)</td>
<td>17.1 ( \pm 0.1)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>( \approx 2.0 ) (c)</td>
<td>—</td>
<td>7.5 ( \pm 0.5)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(-64 \pm 5)</td>
<td>(+8 \pm 2)</td>
<td>70 ( \pm 1)</td>
<td>100 ( \pm 5)</td>
</tr>
<tr>
<td>H I (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>24.53 ( \pm 0.02)</td>
<td>23.2 ( \pm 0.1)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ni I (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>16.4 ( \pm 0.4)</td>
<td>19.5 ( \pm 0.2)</td>
<td>18.6 ( \pm 0.1)</td>
<td>17.4 ( \pm 0.1)</td>
</tr>
<tr>
<td>Mg II (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>18.1 ( \pm 0.1)</td>
<td>19.8 ( \pm 0.1)</td>
<td>18.6 ( \pm 0.3)</td>
<td>18.2 ( \pm 0.1)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>&lt; 4 (d)</td>
<td>—</td>
<td>—</td>
<td>( \approx 2.0 ) (c)</td>
<td>—</td>
<td>13 ( \pm 1)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>(-300 \pm 10)</td>
<td>—</td>
<td>—</td>
<td>(-65 \pm 5)</td>
<td>5 ( \pm 5)</td>
<td>65 ( \pm 5)</td>
<td>131 ( \pm 10)</td>
</tr>
<tr>
<td>Si II (c)</td>
<td>16.7 ( \pm 0.2)</td>
<td>—</td>
<td>—</td>
<td>17.9 ( \pm 0.3)</td>
<td>19.5 ( \pm 0.4)</td>
<td>19.4 ( \pm 0.2)</td>
<td>16.8 ( \pm 0.3)</td>
</tr>
<tr>
<td>Al II (c)</td>
<td>16 ( \pm 1)</td>
<td>—</td>
<td>—</td>
<td>17.3 ( \pm 0.1)</td>
<td>18.2 ( \pm 0.1)</td>
<td>17.5 ( \pm 0.2)</td>
<td>15.5 ( \pm 0.5)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>&lt; 7.6 (d)</td>
<td>—</td>
<td>—</td>
<td>1.1 ( \pm 0.4)</td>
<td>—</td>
<td>7.3 ( \pm 0.3)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>(-300 \pm 5)</td>
<td>—</td>
<td>—</td>
<td>(-72.1 \pm 0.3)</td>
<td>2.8 ( \pm 0.2)</td>
<td>58 ( \pm 1)</td>
<td>89 ( \pm 1)</td>
</tr>
<tr>
<td>Fe II (c)</td>
<td>&gt; 16.7 (d)</td>
<td>—</td>
<td>—</td>
<td>17.5 ( \pm 0.1)</td>
<td>19.3 ( \pm 0.1)</td>
<td>18.47 ( \pm 0.05)</td>
<td>17.56 ( \pm 0.03)</td>
</tr>
<tr>
<td>Ni II (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>16.7 ( \pm 0.2)</td>
<td>17.53 ( \pm 0.02)</td>
<td>17.30 ( \pm 0.03)</td>
<td>16.93 ( \pm 0.07)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3.6 ( \pm 0.6)</td>
<td>—</td>
<td>6.4 ( \pm 0.7)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(-71.4 \pm 0.3)</td>
<td>4.9 ( \pm 0.1)</td>
<td>61.7 ( \pm 0.5)</td>
<td>89 ( \pm 2)</td>
</tr>
<tr>
<td>Si II (c)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>17.7 ( \pm 0.1)</td>
<td>20.6 ( \pm 0.1)</td>
<td>18.78 ( \pm 0.02)</td>
<td>17.8 ( \pm 0.1)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>12.0 ( \pm 0.2)</td>
<td>—</td>
<td>—</td>
<td>2.6 ( \pm 0.6)</td>
<td>—</td>
<td>18 ( \pm 1)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>(-297.6 \pm 0.2)</td>
<td>(-244 \pm 1)</td>
<td>(-124 \pm 3)</td>
<td>(-69 \pm 1)</td>
<td>6 ( \pm 1)</td>
<td>66 ( \pm 2)</td>
<td>132 ( \pm 5)</td>
</tr>
<tr>
<td>C II (c)</td>
<td>17.62 ( \pm 0.03)</td>
<td>17.0 ( \pm 0.1)</td>
<td>(&lt; 16.4 ) (d)</td>
<td>19.2 ( \pm 0.5)</td>
<td>20.00 ( \pm 0.05)</td>
<td>19.10 ( \pm 0.05)</td>
<td>17.4 ( \pm 0.1)</td>
</tr>
<tr>
<td>Si III (c)</td>
<td>17.53 ( \pm 0.02)</td>
<td>16.59 ( \pm 0.03)</td>
<td>15.8 ( \pm 0.2)</td>
<td>16.0 ( \pm 0.1)</td>
<td>19.01 ( \pm 0.05)</td>
<td>18.40 ( \pm 0.06)</td>
<td>16.5 ( \pm 0.1)</td>
</tr>
<tr>
<td>Si IV (c)</td>
<td>17.34 ( \pm 0.01)</td>
<td>16.35 ( \pm 0.07)</td>
<td>15.6 ( \pm 0.3)</td>
<td>15.9 ( \pm 0.2)</td>
<td>17.70 ( \pm 0.01)</td>
<td>17.43 ( \pm 0.01)</td>
<td>15.9 ( \pm 0.1)</td>
</tr>
<tr>
<td>C IV (c)</td>
<td>18.26 ( \pm 0.01)</td>
<td>17.52 ( \pm 0.02)</td>
<td>16.7 ( \pm 0.2)</td>
<td>16.6 ( \pm 0.2)</td>
<td>18.34 ( \pm 0.01)</td>
<td>18.14 ( \pm 0.01)</td>
<td>16.9 ( \pm 0.1)</td>
</tr>
<tr>
<td>N V (c)</td>
<td>16.7 ( \pm 0.1)</td>
<td>16.5 ( \pm 0.2)</td>
<td>(&lt; 16.2 ) (d)</td>
<td>16.5 ( \pm 0.2)</td>
<td>17.30 ( \pm 0.07)</td>
<td>17.2 ( \pm 0.1)</td>
<td>(&lt; 16.7 ) (d)</td>
</tr>
<tr>
<td>( \sigma ) (b)</td>
<td>14 ( \pm 2)</td>
<td>—</td>
<td>—</td>
<td>6 ( \pm 4)</td>
<td>—</td>
<td>40 ( \pm 6)</td>
<td>—</td>
</tr>
<tr>
<td>( v ) (b)</td>
<td>( \approx -297.6 ) (c)</td>
<td>( \approx -244 ) (c)</td>
<td>( \approx -124 ) (c)</td>
<td>( \approx -69 ) (c)</td>
<td>( \approx 6 ) (c)</td>
<td>( \approx 66 ) (c)</td>
<td>( \approx 132 ) (c)</td>
</tr>
<tr>
<td>O VI (c)</td>
<td>17.6 ( \pm 0.1)</td>
<td>17.74 ( \pm 0.05)</td>
<td>17.5 ( \pm 0.1)</td>
<td>16.2 ( \pm 0.2)</td>
<td>18.25 ( \pm 0.03)</td>
<td>18.34 ( \pm 0.08)</td>
<td>17.3 ( \pm 0.1)</td>
</tr>
</tbody>
</table>

(a) The different slab components.
(b) Both the velocity dispersion \( \sigma \) and the LSR \( v \) are in units of km s\(^{-1}\).
(c) The ionic column densities \( N_X \) are in log (m\(^{-2}\)) units.
(d) 2 \( \sigma \) lower / upper limits, respectively.
(e) Fixed parameters.
4.4 Spectral modeling of the ISM

$N_H (\chi^2 > 10)$ due to the over-predicted ionic column densities: $C\, I \sim 3 \times 10^{20} \text{ m}^{-2}$, $Si\, I \sim 4 \times 10^{18} \text{ m}^{-2}$ and $Mg\, II \sim 2.4 \times 10^{20} \text{ m}^{-2}$. The column densities as measured for both $C\, I$ and $Mg\, II$ using the fit with the empirical slab models are much lower (see Table 4.1) and the $Si\, I$ lines are not detected in the spectrum.

A fit with free abundances provides only a partial improvements and the main problems are the high $Si\, II/Si\, I$ and $C\, II/C\, I$ column density ratios. These ratios can be re-

![Graphs showing absorption lines](image)

**Figure 4.4:** Best fit to the HST/COS absorption lines of the cold gas with the slab model (see also Table 4.1).
produced only through the combined effect of a high gas temperature and depletion onto dust. A satisfactory fit is reached when we assume that at least 80% of Mg and 90% of C and Si are depleted from the gaseous phase into dust grains.

The weakly ionized gas of the LVC and IVCs shows rather high temperatures of about 15 000–20 000 K as expected by the significant S II column density and the absence of S I (which cannot be attributed to depletion into dust). This suggests that an important fraction of hydrogen is ionized. Component E, the one at rest, provides 90% of the total \( N_{\text{H}_2} \), while component F is the second strongest but accounts for only \( \sim 5\% \).

The measured \( \sigma_v \) are consistent with those estimated through the \textit{slab} model. The \( \text{H I} \) column densities measured by the two different models are consistent with each other, but their total \( \text{H I} \) column is only about 75% of the value measured at 21 cm (Murphy et al. 1996), which might be due to the high saturation of the UV line or most likely to the difference in beam-size between the 21 cm radio observation and the pencil-beam UV observation. Because the O I 1302.2 Å line is heavily saturated, it is difficult to measure the oxygen abundance. Thus we freeze it to the proto-Solar value. For a complete analysis of the abundances we refer to Sect. 4.4.2, in which we fit the entire UV / X-ray dataset. We have also tested an alternative photo-ionization model for the cold gas and obtained similar results (see Sect. 5.5.1).

A photo-ionized model for the warm ionized gas

To model the warm (mildly) ionized gas responsible for the C II–IV and Si III–IV absorption observed in all velocity components, we tried a collisional ionization model. However, it is not possible to obtain a satisfactory fit with seven collisionally-ionized gas components for any of the HVCs (A to C) and LVC / IVCs (D to G). This is because collisional ionization results in a narrow peak in ionization, while a wide range of ionization states is observed. An alternative solution might be multi-phase CIE gas, which we have tested without obtaining satisfactory results (see Sect. 5.5.1), or cooling gas out of ionization equilibrium (see e.g. Gnat & Sternberg 2007). Here we use a photo-ionization model for the mildly ionized gas, which provides a good solution.

For the photo-ionization modeling we use the \textit{xabs} model in SPEX. The \textit{xabs} model calculates the transmission of a slab of material, where all ionic column densities are linked through a photo-ionization model. The relevant parameter is the ionization parameter \( \xi = L/nr^2 \), with \( L \) the source ionizing luminosity between 1 – 1000 Ryd, \( n \) the density and \( r \) the distance from the ionizing source. Free parameters in the \textit{xabs} model are the hydrogen column density \( N_{\text{H}_2} \), the ionization parameter \( \xi \), the velocity dispersion \( \sigma_v \), the Doppler velocity shift \( v \), and the abundances. We have created a model consisting of seven photo-ionized \textit{xabs} components, one for each velocity component detected. Similar to the \textit{slab} and \textit{hot} models, we have coupled the \( \sigma_v \) and abundances within the two LVC / IVC and HVC groups (see Sect. 4.4.1 and Fig. 4.5), i.e. components A-B-C and E-F-G.

The spectral energy distribution (SED) plays a crucial role in determining the ionization balance in the photo-ionized layers (see e.g. Chakravorty et al. 2009). Unfortunately, the SED which determines the ionization balance of the interstellar gas is not well known. For this reason, we have tested different SEDs on the seven ISM absorbers.
Figure 4.5: Simultaneous fit to the HST/COS and FUSE warm and hot gas components with the slab model (see also Table 4.1).

(see also Fig. 4.6):

1. local emissivity (LE) of all the galaxies and QSOs, i.e. the integrated emission of galaxies and QSOs as seen in the local Universe at $z = 0$;

2. local emissivity (at $z = 0$) of only QSOs;

3. cosmic background radiation plus X-ray background as measured by HEAO1 and BeppoSAX;

4. interstellar field SED (entirely due to starlight);

5. powerlaw (PL) SEDs.

The first three SEDs represent a purely extragalactic ionizing source and have been taken from Haardt & Madau (2001, 2012). The interstellar field SED refers to the one specified in the CLOUDY “Hazy” manual (Ferland 2005). For the last case (SED 5) we have created a grid of powerlaw SEDs ($F_{\nu} \propto \nu^{\alpha}$) with slopes ranging from $-4.0$ to $-0.1$.
Multiwavelength campaign on Mrk 509 IX. The Galactic foreground

Figure 4.6: SEDs which have been used in the fit of the warm photo-ionized gas. Arbitrary units are used in order to compare the shape of the SEDs. LE SED refers to QSO + galaxies. See also Sect. 4.4.1.

with steps of 0.05 and with a low-energy cut-off below 1 Ryd. We calculate the ionization balance through the SPEX \texttt{xabsinput} tool: it receives as input the ionizing SED and the abundances of the gas, and determines the ionization balance using Cloudy version 08.00 (see the SPEX manual for more details). We have used the normalization for the physical SEDs as given in the literature, but we note that the absolute normalization of the SED does not matter while the SED shape does (see e.g. Sect. 6.2 in the SPEX manual). In order to have a sufficiently broad energy band, \texttt{xabsinput} adds a minimum flux value at energies of $10^{-8}$ and $10^9$ Ryd, which does not affect the results.

Because we do not know the abundances a priori, we have decided to fix them to the proto-Solar values of Lodders & Palme (2009). We have adopted the same SED and abundances for the IVC group, and similarly for the HVC group. This choice is suggested by the fact that large deviations in ionization balance and metallicity are mostly expected by comparing LVC / IVCs lying in the Galactic disk with the halo HVCs (see below).

Among the four physically motivated SEDs, only the local emissivity (LE) SED including galaxies plus QSOs provides a satisfactory fit with proto-Solar abundances ($\chi_\nu \sim 1.3$, see Table 4.2) for all seven absorbers. The other physical SEDs do not provide good fits even when allowing for highly non-solar abundances. The powerlaw SEDs provide results similar to the best fitting LE SED. For absorption from both IVCs and HVCs the best fit is obtained by assuming a PL SED with slope $\alpha \sim -2$, and proto-Solar abundances. The main difference between the PL and LE SEDs are the derived $\xi$ values. The ionization parameters are systematically higher for a LE SED (see Table
Table 4.2: Best fit results for the COS spectrum using 7 photo-ionized absorbers with proto-Solar abundances.

<table>
<thead>
<tr>
<th>SED type</th>
<th>A (^{(a)})</th>
<th>B (^{(a)})</th>
<th>C (^{(a)})</th>
<th>D (^{(a)})</th>
<th>E (^{(a)})</th>
<th>F (^{(a)})</th>
<th>G (^{(a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{CIV} )^{(b)}</td>
<td>(-297.6)</td>
<td>(-244)</td>
<td>(-124)</td>
<td>(-69)</td>
<td>(6)</td>
<td>(66)</td>
<td>(132)</td>
</tr>
<tr>
<td>(\sigma_{v} )^{(b)}</td>
<td>11.1 (\pm) 0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_{H} )^{(c)}</td>
<td>(0.44 \pm 0.01)</td>
<td>(0.073 \pm 0.002)</td>
<td>(0.012 \pm 0.002)</td>
<td>(10.0 \pm 0.5)</td>
<td>(19.0 \pm 0.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\log \xi )^{(d)}</td>
<td>-0.56 (\pm) 0.01</td>
<td>-0.51 (\pm) 0.01</td>
<td>-0.51 (\pm) 0.03</td>
<td>-3.00 (\pm) 0.03</td>
<td>-1.70 (\pm) 0.01</td>
<td>-1.70 (\pm) 0.01</td>
<td>-0.56 (\pm) 0.03</td>
</tr>
<tr>
<td>(\alpha_{SED} )^{(e)}</td>
<td>-2.3</td>
<td>-2.3</td>
<td>-2.3</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-2.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>LE (^{(f)})</td>
<td>(N_{H} )^{(c)}</td>
<td>(0.54 \pm 0.01)</td>
<td>(0.064 \pm 0.002)</td>
<td>(0.009 \pm 0.001)</td>
<td>(0.033 \pm 0.001)</td>
<td>(3.61 \pm 0.02)</td>
<td>(2.39 \pm 0.03)</td>
</tr>
<tr>
<td>(\log \xi )^{(d)}</td>
<td>-0.07 (\pm) 0.01</td>
<td>0.20 (\pm) 0.01</td>
<td>0.17 (\pm) 0.08</td>
<td>-2.5 (\pm) 0.1</td>
<td>-1.10 (\pm) 0.01</td>
<td>-1.11 (\pm) 0.01</td>
<td>0.15 (\pm) 0.02</td>
</tr>
</tbody>
</table>

\(^{(a)}\) The different photo-ionized xabs components.
\(^{(b)}\) Both the velocity dispersion \(\sigma_{v}\) and \(v_{CIV}\) are in units of \(\text{km s}^{-1}\). The \(v_{CIV}\) are fixed.
\(^{(c)}\) The hydrogen column densities \(N_{H}\) are in \(10^{23} \text{ m}^{-2}\) units.
\(^{(d)}\) The ionization parameter \(\xi = L/n_{H}r^{2}\) is in units of \(10^{-9} \text{ Wm}\).
\(^{(e)}\) \(\alpha_{SED}\) is the best fitting slope for the PL SED (see also Sect. 4.4.1).
\(^{(f)}\) PL refers to the fit assuming a power-law SED, LE refers to the Local Emissivity SED including galaxies and QSOs.

4.2). Component A is the least ionized of the three HVCs, component D is the least ionized among the four IVCs. Components E and F have the same ionization parameter. We find that HVCs are generally more ionized than the IVCs. The conversion from the ionization parameter \(\xi = L/n_{H}r^{2}\) (as usually defined in the X-rays) to the standard \(U = n_{e}/n_{H}\) (commonly used at lower energies in HVC works) is not trivial and depends on the adopted SED. Examples of conversion factors are provided by Netzer (2008).

As a next step we test for deviations from Solar abundances for both HVCs and IVCs. However, a complete set of accurate abundances can only be obtained by including the X-ray spectrum. Therefore we first discuss the components of the X-ray spectral models, before presenting a model that fits simultaneously FUSE, COS and RGS data and the abundances. We note that the error bars in Table 4.2 are very small, especially for the column densities, due to the quality of the data. However, possible systematic errors, like those due to deviations from proto-Solar abundances, are not included (see e.g. the final complete model in Table 4.5).

4.4.2 X-ray spectral fits

The RGS spectrum of Mrk 509 is shown in detail in paper III. Paper II lists the strongest interstellar lines in this spectrum. In our analysis of this spectrum we adopt the AGN continuum and emission line model given in paper III, as well as the outflow slab model in order to subtract the absorption intrinsic to the AGN. The RGS X-ray spectrum is complementary to the COS-FUSE spectra, providing the column densities of both the weakly and mildly ionized O and Ne ions, which are important to constrain the warm gas. The hot gas mostly absorbs at X-ray wavelengths and can be thoroughly
Table 4.3: Empirical model for the RGS spectrum.

<table>
<thead>
<tr>
<th>Phase</th>
<th>(N_\text{A}/N_E)</th>
<th>(N_\text{B}/N_E)</th>
<th>(N_\text{C}/N_E)</th>
<th>(N_\text{D}/N_E)</th>
<th>(N_\text{E}/N_E)</th>
<th>(N_\text{F}/N_E)</th>
<th>(N_\text{G}/N_E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v (km s(^-1))</td>
<td>(\equiv -298)</td>
<td>(\equiv -244)</td>
<td>(\equiv -124)</td>
<td>(\equiv -69)</td>
<td>(\equiv 6)</td>
<td>(\equiv 66)</td>
<td>(\equiv 132)</td>
</tr>
<tr>
<td>cold</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td>0.009 ± 0.007</td>
<td>(\equiv 1)</td>
<td>0.15 ± 0.01</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>warm</td>
<td>0.6 ± 0.2</td>
<td>0.10 ± 0.05</td>
<td>0.02 ± 0.01</td>
<td>0.017 ± 0.001</td>
<td>(\equiv 1)</td>
<td>0.58 ± 0.05</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>hot</td>
<td>0.22 ± 0.07</td>
<td>0.31 ± 0.06</td>
<td>0.18 ± 0.06</td>
<td>0.009 ± 0.005</td>
<td>(\equiv 1)</td>
<td>1.2 ± 0.3</td>
<td>0.11 ± 0.04</td>
</tr>
</tbody>
</table>

(a) Column density ratios for the cold, warm and hot phases used in the empirical model fit to the RGS spectrum. We normalize the ratios to component E.

studied only in this energy domain. Moreover, some important absorption lines from neutral atoms are often saturated in the UV providing only lower limits to their column densities. In the X-rays the same ions usually provide non saturated lines, but with limited velocity resolution.

An empirical slab model for the RGS spectrum

We first determine the column densities independently of ionization balance as we also did for both COS and FUSE spectra. This is an important check of the column densities for those ions with saturated lines in the UV band, in particular O I and N I. It also gives column densities for ions absent in the UV spectra. Unfortunately, the seven interstellar components which are resolved in the UV spectra, are one blend in the RGS spectrum. This yields degeneracy when fitting the RGS spectrum and we propose the following solution. We create an empirical model with seven slab components as in Sect. 4.4.1, but we freeze the column density ratios to those determined from the UV spectra for the seven velocity components for the cold, warm and hot phases. These column density ratios were determined from non-saturated UV lines. For the cold phase (O I-II) we use the Fe II and S II UV lines. For the warm phase (O III-V) we use C IV and Si IV lines. For the hot phase we use O VI. It is thought that most O VI arises from the conductive layer between the warm and the hot gas, but our physical models predict that in the LOS towards Mrk 509 at least half of the O VI belongs to the hot gas and thus might be a possible indicator for it (see also Sect. 5.5.1). The column density ratios adopted are displayed in Table 4.3. The errors on these average ratios are estimated from the spread in the two column density ratios calculated; for instance, the error on the \(N_F/N_E\) ratio for the cold gas is given by the difference in the respective ratios provided by the Fe II and S II columns. In the case of the hot phase we have adopted just the statistical errors on the O VI column densities because it is the only highly ionized ion (five times ionized or above) present in the UV spectrum.

The LSR velocities of the seven slab components are fixed to the values measured from the UV C IV lines. Moreover, we fix the velocity dispersion to the averages determined with UV slab fits (see Table 4.1). In particular, for the low-ionization absorbers E, F and G we adopt a value of 9 km s\(^-1\), which is the average \(\sigma_V\) of all the weakly ionized species. We did verify that a change of ± 5 km s\(^-1\) in \(\sigma_V\) (the average scatter in
4.4 Spectral modeling of the ISM

\( \sigma_V \) does not affect the column density estimates in the RGS fits.

All ionic column densities that are not constrained by the X-ray data, but have predicted X-ray continuum absorption, are fixed to the values calculated from the COS slab fit. Examples are C\text{I-IV} and Si\text{II-IV}. We also fix the H\text{I} column densities because H\text{I} only produces continuum absorption in the X-ray spectrum and there is no way to disentangle the different kinematics components. We split the total \( N_{\text{H}1} = 4.44 \times 10^{24} \) m\(^{-2} \) (Murphy et al. 1996) into four components representing D–G obtained above for the cold phase. The results of this model are listed in Table 4.4 and discussed in Sect. 5.5.3. We note that only the N\text{I} column densities provided by the RGS fits are larger than those measured in the UV spectra, while the other column densities are consistent for the two different wavelength regions.

A self-consistent physical model of the ISM: simultaneous UV / X-ray spectral fits

We construct a realistic ISM model consisting of a multi-phase structure by extending the UV ISM model. Essentially, we assume that the ISM consists of seven clouds or layers with different speeds but with a similar structure the LVC and IVCs (components D to G) have a cold phase of collisionally-ionized gas and molecules, a warm photo-ionized gas phase and a hot collisionally-ionized gas phase. The HVCs (components A to C) consist only of the warm and hot gas phases as suggested by the absence of high-velocity cold gas in the UV spectrum (see Table 4.5). We simultaneously fit the RGS, COS and FUSE spectra in order to get the highest possible accuracy on line strength and broadening. UV saturated lines are ignored when lines from the same ion are not saturated in the X-ray spectrum. This is the case for the O\text{I} and N\text{I} UV lines at \(+0 \) km s\(^{-1}\) and \(+65 \) km s\(^{-1}\), which are saturated while their X-ray counterparts are not.

We take into account absorption by interstellar dust with the SPEX \textit{amol} component. The \textit{amol} model calculates the transmission of various molecules, for details see Pinto et al. (2010); Costantini et al. (2012) and the SPEX manual. The model currently takes into account the modified edge and line structure around the O and Si K-edge, and the Fe K / L-edges, using measured cross sections of various compounds taken from the X-ray literature.

The velocity dispersion \( \sigma_v \) is coupled within the component groups A-B-C and E-F-G as previously done (see Sect. 4.4.1). The \( \sigma_v \) of component D is still a free parameter as its lines are clearly narrower, especially for O\text{I} (see Fig. 4.1). The LSR velocities are fixed to the values estimated by the C\text{IV} slab fits (see Table 4.1). As in Sect. 4.4.1, the abundances of each gas phase are coupled within component groups A-B-C (HVCs) and D-E-F-G (IVCs). For components C, D and G it is very difficult to measure accurate independent abundances because of their weak and blended profiles, while this is possible for components A, B, E, and F. However, we also do not want to increase the complexity of our model unnecessarily. Thus, we separately fitted the profiles of these latter four strongest components and found that the abundances of components A and B were in good agreement, although less constrained, and the same applies for components E and F. We also decided to keep proto-Solar abundances for all the HVCs because a fit with free abundances does not provide strong constraints besides Si/C \( \gtrsim 1 \). Because in terms of \( \chi^2 \) the physical model provides results as good as those obtained
Table 4.4: RGS spectral fits: empirical model with 7 slab absorbers. All the units are same as in Table 4.1.

<table>
<thead>
<tr>
<th>Par</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν</td>
<td>$\equiv -298$</td>
<td>$\equiv -244$</td>
<td>$\equiv -124$</td>
<td>$\equiv -69$</td>
<td>$\equiv 6$</td>
<td>$\equiv 66$</td>
<td>$\equiv 132$</td>
</tr>
<tr>
<td>σ</td>
<td>$\equiv 12$</td>
<td>$\equiv 18$</td>
<td>$\equiv 2.6$</td>
<td>$\equiv 9$</td>
<td>$\equiv 22.2$</td>
<td>$\equiv 24.6$</td>
<td>$\equiv 23.6$</td>
</tr>
<tr>
<td>HI</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 19.3 \pm 0.06$</td>
<td>$\equiv 19.5$</td>
<td>$\equiv 18.6$</td>
<td></td>
</tr>
<tr>
<td>N I</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 18.7$</td>
<td>$\equiv 18.5 \pm 0.5$</td>
<td>$\equiv 17.8$</td>
<td>$\equiv 17.0$</td>
</tr>
<tr>
<td>N II</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 19.2$</td>
<td>$\equiv 21.4 \pm 0.1$</td>
<td>$\equiv 20.5$</td>
<td>$\equiv 19.6$</td>
</tr>
<tr>
<td>O I</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 17.9$</td>
<td>$\equiv 19.8 \pm 0.3$</td>
<td>$\equiv 19.0$</td>
<td>$\equiv 18.2$</td>
</tr>
<tr>
<td>Ne I</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 18.6$</td>
<td>$\equiv 20.7 \pm 0.1$</td>
<td>$\equiv 19.9$</td>
<td>$\equiv 19.0$</td>
</tr>
<tr>
<td>Ne II</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 18.7$</td>
<td>$\equiv 20.7 \pm 0.1$</td>
<td>$\equiv 19.9$</td>
<td>$\equiv 19.0$</td>
</tr>
<tr>
<td>Mg I</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 18.7$</td>
<td>$\equiv 19.5 \pm 0.2$</td>
<td>$\equiv 19.2$</td>
<td>$\equiv 17.8$</td>
</tr>
<tr>
<td>Mg II</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 18.7$</td>
<td>$\equiv 19.5 \pm 0.2$</td>
<td>$\equiv 19.2$</td>
<td>$\equiv 17.8$</td>
</tr>
<tr>
<td>Fe I</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 17.9$</td>
<td>$\equiv 19.7 \pm 0.3$</td>
<td>$\equiv 18.9$</td>
<td>$\equiv 18.1$</td>
</tr>
<tr>
<td>Fe II</td>
<td></td>
<td></td>
<td></td>
<td>$\equiv 17.8$</td>
<td>$\equiv 19.8 \pm 0.2$</td>
<td>$\equiv 19.0$</td>
<td>$\equiv 18.1$</td>
</tr>
<tr>
<td>C V</td>
<td>18.9</td>
<td>18.1</td>
<td>17.4</td>
<td></td>
<td>17.3</td>
<td>19.1 ± 0.3</td>
<td>18.9</td>
</tr>
<tr>
<td>O III</td>
<td>19.2</td>
<td>18.4</td>
<td>17.6</td>
<td></td>
<td>17.6</td>
<td>19.5 ± 0.2</td>
<td>19.2</td>
</tr>
<tr>
<td>O IV</td>
<td>19.0</td>
<td>18.2</td>
<td>17.5</td>
<td></td>
<td>17.4</td>
<td>19.3 ± 0.3</td>
<td>19.0</td>
</tr>
<tr>
<td>Ne III</td>
<td>19.8</td>
<td>18.9</td>
<td>18.1</td>
<td></td>
<td>18.1</td>
<td>20.0 ± 0.2</td>
<td>19.7</td>
</tr>
<tr>
<td>C VI</td>
<td>18.5</td>
<td>18.7</td>
<td>18.5</td>
<td></td>
<td>17.1</td>
<td>19.2 ± 0.1</td>
<td>19.3</td>
</tr>
<tr>
<td>N VI</td>
<td>18.3</td>
<td>18.5</td>
<td>18.2</td>
<td></td>
<td>16.9</td>
<td>19.0 ± 0.1</td>
<td>19.1</td>
</tr>
<tr>
<td>N VII</td>
<td>18.2</td>
<td>18.3</td>
<td>18.1</td>
<td></td>
<td>16.8</td>
<td>18.9 ± 0.3</td>
<td>19.0</td>
</tr>
<tr>
<td>O VI</td>
<td>18.2</td>
<td>18.3</td>
<td>18.1</td>
<td></td>
<td>16.8</td>
<td>18.9 ± 0.3</td>
<td>19.0</td>
</tr>
<tr>
<td>O VII</td>
<td>19.4</td>
<td>19.6</td>
<td>19.3</td>
<td></td>
<td>17.9</td>
<td>20.14 ± 0.05</td>
<td>20.2</td>
</tr>
<tr>
<td>O VIII</td>
<td>19.0</td>
<td>19.1</td>
<td>18.9</td>
<td></td>
<td>17.5</td>
<td>19.7 ± 0.1</td>
<td>19.8</td>
</tr>
<tr>
<td>Ne IX</td>
<td>18.9</td>
<td>19.0</td>
<td>18.8</td>
<td></td>
<td>17.4</td>
<td>19.6 ± 0.2</td>
<td>19.7</td>
</tr>
<tr>
<td>Ne X</td>
<td>18.5</td>
<td>18.7</td>
<td>18.4</td>
<td></td>
<td>17.0</td>
<td>19.2 ± 0.5</td>
<td>19.3</td>
</tr>
<tr>
<td>Fe XVII</td>
<td>16.6</td>
<td>16.7</td>
<td>16.5</td>
<td></td>
<td>15.3</td>
<td>17.2 ± 0.2</td>
<td>17.3</td>
</tr>
</tbody>
</table>
with the empirical slab model, we prefer to maintain our choice of abundances.

**Metal depletion**

If the cold and warm phases share the same Galactic environment, but have different heating processes, their abundances might be still similar. However, the ratios of the column density estimates that we have reported in Table 4.1 and 4.4 show strong discrepancies between neutral and ionized gas column densities. In particular the C I column density is at least two orders of magnitude smaller than that for C II, while O I-II and N I-II do not show similar trends. It is unlikely that in the cold gas the carbon abundance is orders of magnitude smaller than Solar. The most reasonable explanation is instead that most of the neutral carbon is depleted in dust grains or molecules. The same applies for Fe, Si, Al. There are indeed no detections in the UV spectrum of any of their neutral transitions. Moreover, the Fe column densities are poorly constrained by the RGS slab model (see Table 4.4) due to the weakness of the Fe L-edge (Fig. 4.7). The column densities estimated for oxygen and nitrogen with the diagnostic model are instead close to those predicted for proto-Solar abundances, which suggests that their depletion factors should be much lower than those for C and Fe. We can measure the depletion factors by testing for the presence of CO, H$_2$O ice, silicates and other molecules through the amol model adopted. The depletion of the cold gas phase into dust grains argues in favor of not coupling the abundances of the cold and warm gas for those elements which are expected to be involved like C, O, Mg, Al, Si, Fe, Ni. Instead we couple the abundances of N, Ne and S of the cold and warm gas because these elements are not expected to be highly depleted (Wilms et al. 2000).

**A collisionally-ionized model for the hot ionized gas**

The main difference between the UV ISM model and the final ISM model is the addition of seven collisionally-ionized gas hot components, one for each layer. They will reproduce the highly-ionized gas that we have previously probed with the diagnostic empirical model, see Table 4.4. The only free parameters for each component are the hydrogen column density, the temperature and the velocity dispersion. The Doppler velocities are coupled according to the prescriptions given above. However, here we couple the velocity dispersion of components D–G as they fully blend in all the spectra. A satisfactory fit for the hot gas is reached by assuming proto-Solar abundances for all the seven hot components. Indeed, a fit with free abundances does not provide any significant deviation from the abundances of Lodders & Palme (2009). For this reason we report the results obtained by assuming proto-Solar abundances for the hot gas in Table 4.5. We find that most of the hot gas is at rest and originates from the the slow components E and F. We obtain only upper limits to the column densities of the highly-ionized gas for the other components. We discuss these results in Sect. 5.5.3.
Figure 4.7: Mrk 509 RGS data and best fit for the complete ISM model (see Sect. 4.4.2). All the absorption and emission lines intrinsic to the AGN have been subtracted through the AGN slab model of Detmers et al. (2011). The flux is normalized to the AGN continuum emission. Color code of the labels: red for the hot phase, purple for the warm phase and blue for the cold phase.
### 4.4 Spectral modeling of the ISM

**Table 4.5: UV / X-ray simultaneous fits with the final complete ISM model.**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Par</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ν</td>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ν</td>
<td>–297.6</td>
<td>–244</td>
<td>–124</td>
<td>–69</td>
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<td>66</td>
<td>132</td>
</tr>
<tr>
<td>Cold gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 2</td>
<td>9.6 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N_H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.9 ± 0.1</td>
<td>44 ± 1</td>
<td>8 ± 1</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>–</td>
<td></td>
<td></td>
<td>&lt; 0.6</td>
<td>1.26 ± 0.01</td>
<td>1.24 ± 0.02</td>
<td>2.7 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>C/H</td>
<td>–</td>
<td></td>
<td></td>
<td>&lt; 0.1</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>N/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.8 ± 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O/H</td>
<td>–</td>
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<tr>
<td></td>
<td>Ne/H</td>
<td>–</td>
<td></td>
<td></td>
<td>1.3 ± 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mg/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.41 ± 0.04</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Al/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.06 ± 0.01</td>
<td></td>
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<tr>
<td></td>
<td>Si/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.14 ± 0.04</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>S/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.67 ± 0.01</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Fe/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.07 ± 0.01</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Ni/H</td>
<td>–</td>
<td></td>
<td></td>
<td>0.07 ± 0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.8 ± 0.1</td>
<td>4.7 ± 0.2</td>
<td>18.5 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N_H</td>
<td>0.52 ± 0.01</td>
<td>0.065 ± 0.002</td>
<td>0.010 ± 0.002</td>
<td>0.014 ± 0.002</td>
<td>5.4 ± 0.3</td>
<td>2.9 ± 0.1</td>
<td>0.013 ± 0.002</td>
</tr>
<tr>
<td></td>
<td>logξ</td>
<td>–0.03 ± 0.01</td>
<td>0.17 ± 0.01</td>
<td>0.22 ± 0.08</td>
<td>–2.3 ± 0.2</td>
<td>–1.13 ± 0.01</td>
<td>–1.12 ± 0.01</td>
<td>0.7 ± 0.2</td>
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<tr>
<td></td>
<td>C/H</td>
<td>± 1</td>
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<td></td>
<td>± 1</td>
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<tr>
<td></td>
<td>O/H</td>
<td>± 1</td>
<td></td>
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<td>0.5 ± 0.1</td>
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<td></td>
<td>Al/H</td>
<td>± 1</td>
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<td>0.33 ± 0.08</td>
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<td></td>
<td>Si/H</td>
<td>± 1</td>
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<td>0.60 ± 0.01</td>
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<td></td>
<td>Fe/H</td>
<td>± 1</td>
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<td>0.90 ± 0.06</td>
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<td>&lt; 11</td>
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<td>16 ± 6</td>
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<td></td>
<td>N_H</td>
<td>&lt; 0.3</td>
<td>&lt; 0.4</td>
<td>&lt; 0.5</td>
<td>1.7 ± 0.5</td>
<td>19 ± 3</td>
<td>4 ± 1</td>
<td>&lt; 1</td>
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<td></td>
<td>T</td>
<td>40 ± 10</td>
<td>55 ± 15</td>
<td>51 ± 14</td>
<td>14 ± 1</td>
<td>160 ± 10</td>
<td>70 ± 10</td>
<td>55 ± 15</td>
</tr>
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<tr>
<td></td>
<td>CO</td>
<td>–</td>
<td></td>
<td></td>
<td>–</td>
<td>7.5 ± 1.5</td>
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<tr>
<td></td>
<td>H_2O ice</td>
<td>–</td>
<td></td>
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<td>&lt; 1.0</td>
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</tr>
<tr>
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<td>MgSiO_3</td>
<td>–</td>
<td></td>
<td></td>
<td>–</td>
<td>&lt; 0.8</td>
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<td>Fe</td>
<td>–</td>
<td></td>
<td></td>
<td>–</td>
<td>&lt; 0.6</td>
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</tr>
<tr>
<td></td>
<td>Fe_2O_3</td>
<td>–</td>
<td></td>
<td></td>
<td>–</td>
<td>&lt; 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H_2</td>
<td>–</td>
<td></td>
<td></td>
<td>–</td>
<td>10–50</td>
<td>4–6</td>
<td></td>
</tr>
</tbody>
</table>

(a) Velocity units are same as in Table 4.1. Doppler velocities ν are fixed.

(b) The hydrogen column densities N_H are in units of 10^{22} m^{-2}. The ionization parameter ξ is in units of 10^{-9} Wm.

(c) Abundances ratios are in the linear proto-Solar abundance units of Lodders & Palme (2009).

(d) Molecular column densities are in units of 10^{20} m^{-2}.

(e) H_2 column densities are taken from Wakker (2006).
4.4.3 Alternative models

In this section we report several tests to check the validity and uniqueness of our model.

The first issue concerns the physical state of the cold weakly ionized gas. We have used a collisionally-ionized model in SPEX because at low temperatures this mimics well the cold interstellar gas (see Sect. 4.4.1). However, at these temperatures photo-ionization could also provide a significant contribution. Thus, we tried an alternative model in which four additional photo-ionized \( xabs \) components (E to G) substitute for the cold collisionally-ionized ones. The fit slightly worsens and absolute abundances, i.e. relative to hydrogen, are not well constrained. They show systematic deviations of about 25–50% from the values obtained with the collisionally-ionized model, while abundances relative to oxygen or other well constrained ions have smaller deviations. In summary, a photo-ionized plasma provides a worse fit to the cold phase, but in principle part of the cold component might be photo-ionized.

Excluding \( \text{C}\text{II} \), ions like \( \text{O}\text{I} \)–\( \text{II} \) and \( \text{O}\text{III} \)–\( \text{IV} \) have been put in two different phases in the slab model (see Sect. 4.4.1). Although the physical model takes into account contributions to each ion from any phase, we have to justify the choice adopted for the empirical slab model. At first we chose to fit the \( \text{C}\text{II} \) together with the \( \text{C}\text{IV} \) and \( \text{Si}\text{III} \)–\( \text{IV} \) because it was the only ‘low’ ion clearly showing high-velocity absorption. The physical model validates this choice as most of the carbon in the cold phase turns out to be locked into dust and the bulk of \( \text{C}\text{II} \) comes from the warm photo-ionized phase. For completeness we have tested a photo-ionization model for each velocity component in order to fit the entire set of neutral to doubly ionized ions (and ignoring all the other lines), assuming they are from a warm weakly-ionized phase and decoupled from the remaining more highly ionized ions. However, the fit is worse than before \( (\Delta \chi^2 \sim +1.0) \); the observed \( \text{C}\text{II}/\text{C}\text{I}, \text{Si}\text{II}/\text{Si}\text{III} \) and \( \text{S}\text{II}/\text{S}\text{III} \) column density ratios are not well reproduced. Even if we add dust depletion for carbon and silicon we cannot obtain satisfactory results (at any \( N_{\text{H}} \)).

We have also considered an alternative interpretation of the warm mildly-ionized gas that produces most of \( \text{C}\text{III} \)–\( \text{IV} \) and \( \text{Si}\text{III} \)–\( \text{IV} \). Instead of seven photo-ionized absorbers (see Sect. 4.4.1) we used multiphase collisionally-ionized gas: each velocity component has been fitted with 2 or even 3 CIE components. This model provides the worst fit so far. It might be that the gas is out of equilibrium, but we cannot check this further with the current spectral models in SPEX. However, the goodness of fit of our standard model suggests that photo-ionization is a likely interpretation.

The last important issue concerns \( \text{O}\text{VI} \). We have so far considered this ion, together with \( \text{O}\text{VII} \)–\( \text{VIII} \), as a tracer of the hot highly-ionized gas. However, as we have previously mentioned in Sect. 4.4.2, most of \( \text{O}\text{VI} \) is thought to arise from a cooling colder phase with temperatures \( 1 – 5 \times 10^5 \text{K} \) (see e.g. Richter 2006). Therefore, we have applied a collisionally-ionized model for this conductive phase that produces \( \text{N}\text{V} \) and \( \text{O}\text{VI} \) assuming a temperature of \( 2.1 – 4.4 \times 10^{-2} \text{keV} \) \( (2.5 – 5.1 \times 10^5 \text{K}) \). However, this model is incompatible with another collisionally-ionized phase producing \( \text{O}\text{VII} \)–\( \text{VIII} \). In order to explain the \( \text{O}\text{VIII}/\text{O}\text{VII} \) and \( \text{Ne}\text{X}/\text{Ne}\text{IX} \) ratios this highest-ionization gas also provides at least half of the observed \( \text{O}\text{VI} \). In summary, either half of the \( \text{O}\text{VI} \) is
4.5 Discussion

Our analysis shows that the ISM in the LOS of Mrk 509 has a multi-phase structure (see Table 4.1 and 4.5) and complex dynamics. The ISM structure is similar for the different velocities components A–G, but the LVC and IVCs show a three-phase structure while the HVCs show only two ionized phases. We first discuss the general structure of the ISM that we have probed, its constituents and chemistry. Then, we will characterize the several absorbers, describe their heating processes and locate them in the Galactic environment.

4.5.1 ISM multi-phase structure

In the LOS towards Mrk 509 the ISM is found in different physical and chemical forms. We found the gas at various temperatures with different heating processes. Our UV spectral modeling has revealed a large sample of ionization states (see Table 4.1) which is further enlarged by including the X-ray detected absorption. The velocity dispersion is the same within clouds which belong to the same family, such as the IVCs. We have indeed obtained a very good fit by coupling the velocity dispersion of the LVC and IVC components E, F, and G (see Figs. 4.4 and 4.5). Component D is an exception.

The cold phase

We have successfully modeled the interstellar gas with three main phases (see Table 4.5). For the cold gas we have used a collisionally-ionized gas with low temperatures $kT \sim 0.5 - 2.7$ eV ($6000 - 30000$ K). It provides the bulk of the neutral and low-ionization lines, such as O I–II, N I–II, Fe I–II and S II. We detect the cold gas only for the LVC and IVCs, no neutral gas is found at high speed (see Table 4.1). More than 90% of the neutral gas is provided by the LVC component E. Component F ($V_{\text{LSR}} = 65$ km s$^{-1}$) is the second in order of column density and has an ionization state consistent with the LVC (for both the cold and warm gas), which suggests a similar environment for the two clouds.

In Sect. 4.4.1 we have already shown that the C I column densities are too low with respect to those of O I and N I for the C I / C II ratio to be explained only by heating of the cold gas phase. We also argued that at least 90% of C and Si from the cold phase is locked into molecules and dust grains. We confirm this with the complete physical model detailed in Table 4.5. We have indeed obtained a 2$\sigma$ upper limit of 0.1 for both the carbon and silicon abundances with respect to the proto-Solar value of Lodders & Palme (2009). This strongly suggests the presence of both carbonaceous and silicate compounds in the LOS. We have thus tested all the molecules available in the SPEX...
database and found the best match using a significant column of CO (note the feature at 23.2 Å in Fig. 4.7). We get only upper limits for metallic iron, pyroxene (MgSiO₃), and hematite (Fe₂O₃). We are only able to detect dust at rest (component E). Moreover, the broad profile of dust and its nearness to AGN intrinsic features makes the detection of weak lines due to dust at different velocities difficult in the RGS spectrum. It is possible to estimate the CO/H₂ ratio in the LOS of Mrk 509 by comparing our CO column density estimate with the H₂ value measured by Wakker (2006), see also Table 4.5. We obtain CO/H₂ ∼ 0.3 (0.1 – 0.6), which is unusually high for the diffuse ISM. However, we cannot be highly confident in this value as the CO line falls in a wavelength range which is strongly affected by emission and absorption features intrinsic to the AGN (see paper III).

The warm phase

The warm phase consists of mildly-ionized gas in photo-ionization equilibrium. It spreads between several ionization states as it provides most C II-IV and N V. In Sect. 4.4.1 we tested several reasonable SEDs as photo-ionizing source for all the seven clouds. We obtained satisfactory fits only by taking into account the contribution from QSOs together with the extragalactic emission at Z = 0 (Haardt & Madau 2012). The fit with the SED containing only stellar light is not acceptable because this SED is not able to produce the high C IV columns, which we have independently measured with the slab model (see Table 4.1). The total local emissivity (galaxies plus quasars, LE) is the only SED able to photo-ionize the interstellar gas up to the level observed. We have also tested a diagnostic power-law (PL) SED and constrained ionization parameters ξ which are systematically lower than those estimated with the physical LE SED (see Table 4.2). This might be due to the excess in softer part of the LE with respect to the PL SED caused by the additional extragalactic emission. The warm gas is the interstellar component which is best detected at high velocities (see Fig. 4.3).

The hot phase

The hot phase is characterized by highly-ionized gas with temperatures of 50 – 160 eV, i.e. 0.58 – 1.9 × 10⁶ K, (see Table 4.5). It is responsible for the entire O VI-VIII, N VI-VII, Ne IX and C VI absorption (Fig. 4.7). We detect hot gas in both HVCs, LVC and IVCs through the UV O VI lines (see Fig. 4.5). Most of the hot gas is provided by the slow components E and F. The hot phases of the IVCs and HVCs show lower temperatures, closer to that of an O VI interface between the warm and the hot gas, while the temperature of the LVC hot phase is in agreement with that of the typical hot coronal gas of the Galaxy (see e.g. Yao & Wang 2005). In X-rays components A-C merge with D-G and we can only measure upper limits for the column densities of the individual kinematic components (see Table 4.5). We have measured large O VI column densities in the FUSE spectrum (Table 4.1) for components A-C. The high column densities of ionized gas and the non-detection of neutral gas suggest that components A-C should be mostly or entirely ionized by both UV/X-ray background and collisions with the halo of our Galaxy or the Local Group.
In order to estimate the location of the hot gas of components E and F we perform a test on the 620 ks MOS 1-2 data (paper I). We selected an annular region between 10-12' around Mrk 509 in both the MOS detectors and obtained their spectra. We have fitted the 0.5–1.0 keV MOS spectra with a power-law continuum and three Gaussians to describe the O\textsc{vii}-viii and N\textsc{vii} emission lines. The counts and fluxes are corrected for vignetting. The line fluxes in photons m$^{-2}$ s$^{-1}$ sr$^{-1}$ are: $f_{\text{O\textsc{vii}}} = (4.50 \pm 0.35) \times 10^4$, $f_{\text{O\textsc{viii}}} = (1.39 \pm 0.15) \times 10^4$, $f_{\text{N\textsc{vii}}} = (1.11 \pm 0.12) \times 10^4$. From the O\textsc{viii} / O\textsc{vii} line ratio we estimate that the hot gas has an average temperature of 0.186 ± 0.006 keV, which is close to that of component E (see Table 4.5). For a source with a solid angle of 1 sr, at a nominal distance of 10$^{22}$ m, with the observed flux given by the O\textsc{viii} lines, at the measured temperature above, we obtain a CIE emission measure $Y = 1.024 \times 10^{70}$ m$^{-3}$. The emission measure is also given by $Y = (n_e/n_{\text{Hi}}) n_{\text{Hi}}^2 A dR$, where $A = 10^{44}$ m$^2$ is the surface area, $V = A dR$ the volume, $n_e/n_{\text{Hi}} = 1.198$, and $dR$ is the depth of the gas layer. We derive $n_{\text{Hi}} dR = (8.5 \pm 0.9) \times 10^{25}$ m$^{-6}$ m, which does not depend on the adopted distance.

We consider three scenarios - In our first scenario, the gas emitting O\textsc{vii} and O\textsc{viii} is the same gas responsible for the high ionization absorption. This gas then provides the column density that we have measured for the absorption (Table 4.5) and the emission lines. The counts and fluxes are corrected for vignetting. The line fluxes in photons m$^{-2}$ s$^{-1}$ sr$^{-1}$ are: $f_{\text{O\textsc{vii}}} = (4.50 \pm 0.35) \times 10^4$, $f_{\text{O\textsc{viii}}} = (1.39 \pm 0.15) \times 10^4$, $f_{\text{N\textsc{vii}}} = (1.11 \pm 0.12) \times 10^4$. From the O\textsc{viii} / O\textsc{vii} line ratio we estimate that the hot gas has an average temperature of 0.186 ± 0.006 keV, which is close to that of component E (see Table 4.5). For a source with a solid angle of 1 sr, at a nominal distance of 10$^{22}$ m, with the observed flux given by the O\textsc{viii} lines, at the measured temperature above, we obtain a CIE emission measure $Y = 1.024 \times 10^{70}$ m$^{-3}$. The emission measure is also given by $Y = (n_e/n_{\text{Hi}}) n_{\text{Hi}}^2 A dR$, where $A = 10^{44}$ m$^2$ is the surface area, $V = A dR$ the volume, $n_e/n_{\text{Hi}} = 1.198$, and $dR$ is the depth of the gas layer. We derive $n_{\text{Hi}} dR = (8.5 \pm 0.9) \times 10^{25}$ m$^{-6}$ m, which does not depend on the adopted distance.

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In our second scenario, the emitting and absorbing plasmas are decoupled and have different location. Generally, both the Local Hot Bubble (LHB), the diffuse Galactic disk/halo and extragalactic background provide important and different contributions (see e.g. Kaastra et al. 2008; Wang 2009). The LHB is important at lower temperatures with a significant O\textsc{vii} 1s-1p emission line at 0.57 keV. Most of the observed O\textsc{viii} emission belongs to the hot gas of the Galactic disk and halo, which is hotter than the LHB. Extragalactic sources provide the bulk of the X-ray background emission above 0.7 keV. For instance, if we assume that the emitting gas has a density of 10$^4$ m$^{-3}$ (a common value in the local ISM) and $n_{\text{eml}}/n_{\text{abs}} \sim 100$, we obtain that the emitting region has a depth of a few tens of parsec, close to the LHB. According to this scenario, most of the O\textsc{vii} emission originates from the Local Hot Bubble, while the bulk of the absorption would be due to the diffuse hot interstellar gas present in the Galactic disk and halo. This means that our absorption measures are consistent with a Galactic origin for the interstellar clouds in the LOS towards Mrk 509 (and not WHIM) in agreement with previous UV work (Savage et al. 2003; Sembach et al. 2003; Collins et al. 2004).

We can probe the hot gas structure and location with a third alternative way. Fol-
Table 4.6: Column densities comparison for LVC component E.

<table>
<thead>
<tr>
<th>Par</th>
<th>Method 1(^{(b)})</th>
<th>Method 2(^{(c)})</th>
<th>Method 3(^{(d)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N I (^{(a)})</td>
<td>19.5 ± 0.2</td>
<td>20.27 ± 0.06</td>
<td>20.44 ± 0.06</td>
</tr>
<tr>
<td>O I (^{(a)})</td>
<td>21.1 ± 0.2</td>
<td>21.4 ± 0.1</td>
<td>21.05 ± 0.08</td>
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<tr>
<td>Mg II (^{(a)})</td>
<td>19.8 ± 0.1</td>
<td>&lt; 20.7</td>
<td>19.83 ± 0.05</td>
</tr>
<tr>
<td>Fe II (^{(a)})</td>
<td>19.3 ± 0.1</td>
<td>&lt; 19.8</td>
<td>19.00 ± 0.07</td>
</tr>
<tr>
<td>O VI (^{(a)})</td>
<td>18.25 ± 0.03</td>
<td>18.9 ± 0.3</td>
<td>18.31 ± 0.08</td>
</tr>
</tbody>
</table>

\(^{(a)}\) The column densities \(N_X\) are in log (m\(^{-2}\)) units.

\(^{(b)}\) Method 1 is the UV slab model in Table 4.1.

\(^{(c)}\) Method 2 refers to the X-ray slab model in Table 4.4.

\(^{(d)}\) Method 3 gives the predictions of the physical model (Table 4.5).

Following Yao et al. (2009b) we predict the O\(\text{VII-VIII}\) line emission and column densities using their vertical exponential Galactic disk model. In their model, the gas density decays exponentially as a function of the height above the Galactic plane with a scale height of 2.8 kpc and a central value of \(1.4\times10^3\) m\(^{-3}\), and the temperature has a scale height of 1.4 kpc and a central value of \(3.6\times10^6\) K. Their model parameters have large uncertainties, but can still provide useful constraints. Assuming a Galactic latitude of 30 degrees, on average this model predicts column densities of \(\text{O\(\text{VII}\)} = 6.2\times10^{19}\) m\(^{-2}\) and \(\text{O\(\text{VIII}\)} = 2.3\times10^{19}\) m\(^{-2}\), originating from within a few kpc range from the Galactic plane. These column densities might contribute up to the 50% of the absorbing hot gas in our LOS (see Table 4.4). The remaining \(\gtrsim 50\%\) of highly-ionized gas should belong to the more distant Galactic halo and the circumgalactic medium (CGM) and/or to the WHIM.

### 4.5.2 ISM column densities

Most of the UV and X-ray interstellar lines in our spectra are not trivial to disentangle. The component groups HVCs (A, B, C), IVCs (D, F, G) and LVC (E) provide smooth profiles, especially in the X-ray band where their blended profiles appear like a single line. In UV, the HVCs are well separated from the IVCs. However, each component produces only a handful of strong and not heavily saturated lines like those of Fe II, Si II and C IV (see Figs. 4.1, 4.2 and 4.3). The lines in the X-ray spectrum are not saturated, but due to the lower resolution the different velocity components form one blend. Moreover, both the emission and absorption lines intrinsic to the AGN partly affect the interstellar spectral range we fitted (see paper II).

We have computed the ionic column densities predicted by the three different models (see Table 4.6). We compare only the results obtained for component E, as this component provides the best constrained column densities and actually they are the only
4.5 Discussion

Table 4.7: Total abundances for the cold and warm phases of IVCs.

<table>
<thead>
<tr>
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<th>Cold gas</th>
<th>Cold phase</th>
<th>Warm phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/H (^{(a)})</td>
<td>&lt; 0.1</td>
<td>0.7 ± 0.1</td>
<td>equivalent 1</td>
</tr>
<tr>
<td>N/H (^{(a,c)})</td>
<td>0.8 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>O/H (^{(a)})</td>
<td>0.5 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>0.5 ± 0.1 (±0.4) (^{(e)})</td>
</tr>
<tr>
<td>Ne/H (^{(a,c)})</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>Mg/H (^{(a,c)})</td>
<td>0.41 ± 0.04</td>
<td>≤ 1.0 (^{(d)})</td>
<td>0.4 – 1.0</td>
</tr>
<tr>
<td>Al/H (^{(a)})</td>
<td>0.06 ± 0.01</td>
<td>≤ 1.3 (^{(d)})</td>
<td>0.33 ± 0.08 (±0.3) (^{(e)})</td>
</tr>
<tr>
<td>Si/H (^{(a)})</td>
<td>0.14 ± 0.04</td>
<td>≤ 0.62 (^{(d)})</td>
<td>0.60 ± 0.01</td>
</tr>
<tr>
<td>S/H (^{(a,c)})</td>
<td>0.67 ± 0.01</td>
<td>0.67 ± 0.01</td>
<td>0.67 ± 0.01</td>
</tr>
<tr>
<td>Fe/H (^{(a)})</td>
<td>0.07 ± 0.01</td>
<td>≤ 1.0 (^{(d)})</td>
<td>0.90 ± 0.06</td>
</tr>
<tr>
<td>Ni/H (^{(a,c)})</td>
<td>0.07 ± 0.01</td>
<td>≤ 1.8 (^{(d)})</td>
<td>0.7 – 1.8</td>
</tr>
</tbody>
</table>

\(^{(b)}\) The cold phase includes cold gas and molecules from Table 4.5.
\(^{(c)}\) Cold and warm phase abundances are coupled.
\(^{(d)}\) Molecules and dust predicted upper limits.
\(^{(e)}\) Systematic errors (see also Sect. 4.5.3).

free parameters in the RGS fits. The reason for using an empirical model for both the UV and X-ray spectra is to identify discrepancies due to saturation between the UV and X-ray determined ionic column densities. The UV (Method 1) and X-ray (Method 2) column densities are mostly consistent (see Table 4.6). Higher values for N\(^{I}\) and O\(^{VI}\) column densities are obtained from the RGS spectrum. The column in UV for N\(^{I}\) is clearly under-estimated because of saturation as confirmed by the different line ratios of the components E and F in the 1200 Å triplet (see Figs. 4.1 and 4.4). The O\(^{VI}\) column density discrepancy is smaller, about 2σ. The difference is most likely due to the weakness of the O\(^{VI}\) 1s-2p line at 22 Å and the spectral noise (see Fig. 4.7). Apart from the already discussed N\(^{I}\), the UV/X-ray model (Method 3) provides column densities consistent with the UV slab model.

4.5.3 ISM abundances

The ISM abundances are computed by taking into account the contribution from gas, dust and molecules. A thorough and accurate analysis can be done only for the rest frame component, which is detected in all gas and molecular phases (see Table 4.5). We sum the gas and dust contributions to the cold phase for component E, calculate the total abundances and compare them to those of the warm phase in Table 4.7.

There are some limitations to determining the abundances, for instance the nondetection of aluminates allows us only to give the gas contribution to the aluminum abundance. Aluminates absorption features are weak and a fit of the O K edge with additional FeAl\(_2\)O\(_4\) just provides an upper limit to the aluminum abundance of about 1.3 in units of Lodders & Palme (2009), see Table 4.7. The CO column density can be
estimated, while for the other molecules only upper limits are obtained. Thus, we can give only the predicted upper limits to the abundances of Mg, Si, and Fe. Moreover, Mg cannot be detected in the warm phase because most Mg II is already provided by the cold gas, and intermediate-ionization ions do not provide relevant absorption lines in our energy domain, thus its abundance has been coupled to that of the cold gas (see also Sect. 4.4.2). The same applies to Ni, for we have tested a fit with additional NiO molecules, which have provided an upper limit to the nickel abundance of about 1.8. As mentioned above the abundances of N, Ne and S have been coupled between the two phases as those elements are not suspected to be depleted from the cold phase into dust grains.

A comparison between the cold and the warm phases is worthwhile despite these limitations. First, we find consistent abundances for O, Si and Fe for both phases once dust is accounted for. The total iron and nitrogen abundance is close to the proto-Solar value. Differently, $\alpha$ elements like O, Al, Si and S appear to be under-abundant. The Si and S abundance measurements have a high confidence due to the several lines that have been used. The Al and O abundances might be underestimated. The Al column density has been measured with the 1670.8 Å absorption line which is heavily saturated. If we fit the Al absorption line by ignoring its saturated bottom, we get a systematic error on the abundance of about 0.3, i.e. about 100% (see Table 4.7). The oxygen low-ionization lines are highly affected by the AGN intrinsic features. Indeed, within 1$\sigma$ error of the AGN model (see paper III) we obtain a systematic error on the ISM oxygen abundance of 0.4 for the warm gas. We might also miss some additional contribution to the ISM oxygen from molecules as previously discussed (see Sect. 4.5.1). The carbon abundance in the cold phase appears to be lower than in the warm phase, which likely means that we miss some additional molecules like hydrocarbons. Models predict an optical depth of about 0.1 at 43 Å, but here the S/N ratio is too low even for the LETGS spectrum in order to measure column densities (see paper V). Neon is the only over-abundant element, which might suggest that the proto-Solar Ne abundance we use is under-estimated (see e.g. Drake & Testa 2005; Pinto et al. 2010).

Unfortunately statistics are not high enough to estimate the abundances of the hot ionized gas because its lines are much weaker than those of the cold and warm gas. We note, however, that the high-ionization phase can be well fitted by adopting proto-Solar abundances.

4.5.4 The characteristics of LVC, IVCs and HVCs

The separation between IVCs and HVCs is justified if we compare the properties of the two groups (see Table 4.5). The HVCs are clouds highly ionized by both UV / X-ray background photons and collisions with the surrounding hot gas. Neutral gas is absent at these high speeds in this LOS. The HVCs show proto-Solar Si / C ratio, while the IVCs have a carbon excess. Moreover, the ionization parameters $\xi$ of the HVC warm gas are higher than those of the IVCs (see also Fig. 4.9). If the clouds are effectively photo-ionized by the same QSO / Galactic SED, consistent with our best-fit results, this might suggest that the slow components E and F are in a region closer to the Galactic disk, where less UV and X-ray photons penetrate.
4.5 Discussion

LVC location: metallicity method

In order to locate the interstellar absorbers we can compare our measurement of the iron abundance with the Galactic metallicity gradient (see also Pinto et al. 2010). We use the abundance for the warm phase of component E as it is well constrained. We adopt a Galactic altitude of zero for the Sun as it is less than 30 pc distant from the Galactic plane, which is much smaller than the kpc scales we are interested in. If $A_X$ is the abundance of element $X$ in an interstellar cloud, $r$ the difference between the Galactocentric radii of the cloud and that of the Sun, and $h$ the cloud altitude, then the abundance change in the line of sight can be written as

$$
\Delta A = r \frac{dA}{dr} + \frac{dA}{dh} h.
$$

(4.1)

The radial and vertical dependence of the abundance can be expressed as $A_r = A_\odot 10^{\alpha_r r}$ and $A_h = A_\odot 10^{\alpha_h h}$ (see e.g. Pedicelli et al. 2009), where $\alpha_r$ and $\alpha_h$ are the radial and vertical slopes of the abundance gradient, and $A_\odot$ is the proto-Solar value (Lodders & Palme 2009). We estimate the slopes by calculating the average metallicity values found in the literature (Yamagata & Yoshii 1994; Maciel & Costa 2009; Pedicelli et al. 2009; Chen et al. 2011). We find $\alpha_r \sim -0.06$ and $\alpha_h \sim -0.11$ for iron, which means that the vertical gradient is steeper than the radial one. From Eq. (4.1) we obtain

$$
\frac{A}{A_\odot} = \left(\alpha_r r \cdot 10^{\alpha_r r} + \alpha_h h \cdot 10^{\alpha_h h}\right) \cdot \ln 10 + 1.
$$

(4.2)

Through Eq. (4.2) we calculate the Fe abundances for a grid of distances $d$ starting from 0.1 kpc and compare them with our Fe abundance measurement for the warm gas of component E (see Table 4.7). This provides $d \leq 0.5$ kpc for component E, which means that the bulk of the warm interstellar absorption is local and belongs to the Galactic disk. The cold gas exactly follows the kinematics of the warm gas and thus is co-located in the Galactic disk as well.

LVC and IVCs location: kinematics method

It is possible to probe the location of the LVC and IVCs by comparing their LSR velocities with the Galactic rotation. For HVCs this is not possible as their LSR velocities are outside the observed range for Galactic rotation. In Fig. 4.8 we show the rotation curve of the Galaxy as function of the distance as measured in the LOS towards Mrk 509 (see chapter 9 of Binney & Merrifield 1998).

Component E, with $v_{\text{LSR}} = 0 - 10$ km s$^{-1}$ (see Table 4.1), is consistent with distances of $0 - 1$ kpc or $13 - 15$ kpc. However, we note that the density strongly decreases with the height from the Galactic plane. At a distance of 14 kpc along the LOS of Mrk 509, the height above the Galactic plane is 7 kpc, where there is much less neutral gas as within a few hundred pc from the Galactic plane. This would imply that component E is thus < 1 kpc far away, consistent with our earlier conclusion in Sect. 4.5.4.

Component F shows velocities of $60 - 70$ km s$^{-1}$ and for the same reason, namely the decrease in density, it must be at a distance of $4 - 6$ kpc. The large distance from both the
Earth and the Galactic plane is confirmed by the smaller neutral column densities of component F, which are lower than those of component E by at least an order of magnitude (see Table 4.1). The small distance between component E and F also explains why a very good fit is obtained by adopting the similar abundances, temperatures and ionization parameters found for both clouds (Table 4.5).

The location of the remaining two IVCs is not as easy to determine because the uncertainties are larger. If component D ($v_{\text{LSR}} \sim -65 \text{ km s}^{-1}$) belongs to the Galactic corotating gas, then it must have a distance of $25 - 30 \text{ kpc}$ (residing at the other side of the Galaxy) and a height from the plane larger than $12 \text{ kpc}$, which explains why its column densities are two orders of magnitude lower than those for component E.

It is more difficult to determine the position of component G. Fitting the different ions has shown a spread of about $40 \text{ km s}^{-1}$ in the measured velocities. Fe II and S II are consistent with $v_{\text{LSR}} = 90 \text{ km s}^{-1}$, while most ions show velocities near $130 \text{ km s}^{-1}$ (see Table 4.1). The spread is larger than the COS wavelength calibration uncertainties and seems to suggest a double nature of component G. The smallest contribution might refer to corotating gas moving at $\sim 80 - 90 \text{ km s}^{-1}$ with a distance of $6 - 8 \text{ kpc}$. The bulk of component G is represented by the warm phase and moving with a velocity consistent in modulus with those of the HVCs. Unfortunately, the signal-to-noise ratio is small for component G and the $\chi^2$ does not significantly change by dividing this component into two subcomponents, one at 90 and the other at $130 \text{ km s}^{-1}$. If the fast component refers to a Galactic fountain, then it should be close to the Galactic plane as these fountains are expected to reach heights of at most a few kpc. In fact, the high temperatures measured for the cold and warm gas of component G might be signatures of shocks due to interaction with its surrounding (see Table 4.5). An alternative explanation for component G is that it is part of a captured extragalactic cloud, although a satisfactory fit is obtained assuming the same abundances as for Galactic components D, E, and F.

HVCs location: ionization structure

A different approach is required to determine the location of the three HVCs (components A, B and C). All three components have been successfully modeled by adopting the same abundances and photo-ionizing source, extra collisional ionization, and a high ionization state. Interestingly, no sign of fast neutral gas was detected along this LOS, but Sembach et al. (1999) found evidence for H I 21 cm emission at these velocities at a distance of about 2 degrees from Mrk 509. One plausible scenario is that the three ionized HVCs are the outskirt of one large captured cloud, maybe matter stripped from a satellite galaxy, which has fallen into the gravitational well of the Milky Way (see also Fig. 4.10). The hot collisionally-ionized gas suggests that the cloud is impacting the halo of the Galaxy or the Local Group. The fastest cloud, component A, is less ionized than the other 2 HVCs, possibly because it is more distant and thus has currently a smaller interaction with the Galactic halo. This implies that the interaction causes the infalling gas to slowdown.
4.5 Discussion

Figure 4.8: Rotation curve of the Galaxy in the LOS towards Mrk 509 (see Sect. 4.5.4). The velocities of the LVC and IVCs are also displayed.

Figure 4.9: Ionization parameter versus average velocity for the ISM warm phase of the seven cloud systems (see also Table 4.5).
Equilibrium in the interstellar clouds forest

Here we propose the stability curve as an alternative method to probe the dynamical structure of the ISM and to test whether some of the components are co-located. This curve shows the relation between the temperature $T$ of the gas and its pressure $\Xi$, which is commonly defined as

$$\Xi = \frac{4\pi r^2 c_p}{L} = \frac{\xi}{6\pi ckT}. \quad (4.3)$$

This curve was calculated using the SPEX xabsinput tool in the computation of the ionization balance of the photo-ionized warm phase (see Sect. 4.4.1, LE SED) and it is displayed in Fig. 4.11 together with the values calculated for components A–G. This curve divides the $T$ – $\Xi$ plane in two regions: in the region below the curve the heating dominates the cooling, while above the curve the cooling dominates the heating (Krolik et al. 1981). The curve segments which have positive slopes are stable against thermal perturbations, while those with a negative slope are not. Moreover components which have the same $\Xi$ value on this curve are in pressure equilibrium and are thus likely part of the same interstellar structure.

Apparently, all the seven clouds are on stable branches of the curve (see Fig. 4.11). Apart from component G, which is not well constrained, the LV C (E), IVCs (D, F and G) and HVCs (A, B and C) show a rather different $\Xi$ value. As expected the IVC and HVC groups have a different nature and are not co-located. Components E and F share the
4.5 Discussion

Figure 4.11: Stability curve for the LE SED. The values for all the warm photo-ionized components A–G are also displayed (see Sects. 4.4.1 and 4.5.4).

same $\Xi$ and are thus supposed to belong to the Galactic disk environment as we have previously shown. Component D differs from all the others and should not coexist with them. As expected, HVC components A, B and C have quite similar $\Xi$, which means that they might belong to the same structure. The uncertainty on the $\Xi$ value, due to the large error in the $\xi$ value, makes the results for component G uncertain.

4.5.5 Comparison with previous results

Although the interstellar clouds show a different nature and origin in the LOS towards Mrk 509, we have proved that the ISM structure is well described by three phases with different ionization states (see Sect. 4.4.2). The cold phase is a blend of molecules, dust and low-ionization gas, and is not detected in the HVCs. The warm phase is characterized by mildly ionized gas in photo-ionization equilibrium and is present in both HVCs and IVCs. The hot phase is characterized by collisional ionization. These results agree well with the current state of the art (Ferrière 2001) as well as with what was found by Pinto et al. (2010) in the LOS towards GS 1826–238, which is a LMXB located near the Galactic Center. This means that the ISM of the Galaxy follows a certain equilibrium on Galactic scales due to its cooling and heating processes.

We have measured the column densities of the different phases for all the seven cloud systems (see Table 4.1) and compared with those found in the literature. Within the errors, our estimates agree well with the column densities found by previous work (Sembach et al. 1995, 1999, 2003; Collins et al. 2004; Shull et al. 2009). Our O VI column
densities for the HVCs A–C and the IVC G agree within 1σ with those measured by Fox et al. (2006), who take into account the H\textsubscript{2} absorption, which affects this wavelength range (see Fig. 4.5). They consider the blend of components A and B as one absorber, but their column density estimate matches the sum of the values that we have obtained separately for components A and B. Our total H\textsubscript{I} column density differs from the value measured at long wavelengths (see Sect. 4.4.1). This is most likely due to the difference between the beam-size of the UV and radio observations.

Our determination of the location of the different clouds agrees with previous work, but improves upon the previous results. As discussed in Sect. 4.5.4, the HVCs (A–C) are likely at the outskirts of an extragalactic cloud captured by the Galaxy or the Local Group and interacting with them as suggested by Sembach et al. (1999). Component B has a |v| lower than component A maybe due to a stronger impact with the Galactic hot gas, as suggested by its higher ionization state. This might indicate that the external layers of the cloud slewdown during the infall, in agreement with the scenario proposed by Lehner & Howk (2011). Such clouds, known also as VHVCs (see Sect. 5.1), are thought to lose their H\textsubscript{I} and a significant amount of speed during the infall and interaction with the Galaxy. Moreover, from the similar total pressure and temperature properties measured for the warm phase, we conclude that they likely belong to the same cloud structure (see Fig. 4.11). Components E (∼ 0 km s\textsuperscript{-1}) and F (∼ 60 km s\textsuperscript{-1}) have very similar properties for their cold and warm phases and clearly correspond to interstellar gas which follows the Galactic rotation and are expected to reside at less than 1 and 5 kpc, respectively (see Fig. 4.8 and Sect. 4.5.3). This is fully consistent with the conclusions by Blades & Morton (1983). Component D (∼ −60 km s\textsuperscript{-1}) is most likely located off the Galactic plane as previously suggested by Morton & Blades (1986), but should be located at high altitudes.

4.6 Conclusion

We have presented a complete analysis of the interstellar and circumgalactic medium towards the AGN Mrk 509, which is a bright X-ray source with a high Galactic latitude of about −30°, through high-quality grating spectra taken with XMM-\textit{Newton} / RGS, HST / COS and FUSE.

- On average the ISM, as found in the form of LVCs and IVCs near the Galactic disk, preserves a structure consisting of three distinct main phases with different ionization states. HVCs, which usually probe the halo and CGM, have a different structure and in the LOS towards Mrk 509 they show two main phases.

- We have probed seven different cloud systems along the LOS. Our study of their kinematics and abundances has revealed the nature and location of the clouds with respect to the Galactic environment assuming Galactic rotation.

- The HVCs (components A–C) are highly ionized most likely as the result of a larger exposure to the X-ray background and the interaction with the circumgalactic medium. The similar abundances and ionization structure suggest a
common origin for these HVCs. They might be at the outskirt of an extragalactic cloud captured by the Galaxy.

- The LVC (component E) and IVC (component F) refer to interstellar gas co-rotating with the Galactic disk, as confirmed by the detection of dust and molecules at rest wavelengths.

- The location of the IVCs (components D and G) is not well constrained, they might belong either to disk co-rotating gas or to Galactic fountains.

- The column densities, ionization states and locations probed by our alternative models/methods agree with each other and with the results in the literature. All this supports our research method and justifies extension to more lines-of-sight and/or new observations. These analyses will provide indeed a better mapping of the ISM and a deeper study of its chemical composition and interaction with the entire Galaxy.

Acknowledgements

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Multiwavelength campaign on Mrk 509 IX. The Galactic foreground
ISM composition through X-ray spectroscopy of LMXBs

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Abstract

The diffuse interstellar medium (ISM) is an integral part of the evolution of the entire Galaxy. Metals are produced by stars and their abundances are the direct testimony of the history of stellar evolution. However, the interstellar dust composition is not well known and the total abundances are yet to be accurately determined. We probe ISM dust composition, total abundances, and abundance gradients through the study of interstellar absorption features in the high-resolution X-ray spectra of Galactic low-mass X-ray binaries (LMXBs). We use high-quality grating spectra of nine LMXBs taken with XMM-Newton. We measure the column densities of O, Ne, Mg, and Fe with an empirical model and estimate the Galactic abundance gradients. The column densities of the neutral gas species are in agreement with those found in the literature.
We find that solid oxygen is mostly provided by ices and silicates. Respectively, 15–20% and 70–90% of the total amount of O and Fe is found in dust. The dust amount and mixture seem to be consistent along all the lines-of-sight (LOS). Our estimates of abundance gradients and predictions of local interstellar abundances are in agreement with those measured at longer wavelengths. Our work shows that X-ray spectroscopy is a very powerful method to probe the ISM. For instance, on a large scale the ISM appears to be chemically homogeneous showing similar gas ionization ratios and dust mixtures. The agreement between the abundances of the ISM and the stellar objects suggests that the local Galaxy is also chemically homogeneous.

5.1 Introduction

The interstellar medium (ISM) is one of the most important component of galaxies because it influences their evolution: the ISM is enriched with heavy elements by stellar evolution, and it provides the source of material for following generation of stars. There are several physical processes that alter the metallicity of the ISM. Stellar winds and supernovae expel part of the interstellar gas out of the Galactic disk, but gravity generally forces the gas to fall back through the process known as “Galactic fountain” (Shapiro & Field 1976). Gas accreted from smaller galaxies, like the Magellanic Clouds, and the intergalactic medium increases the reservoir of low metallicity gas. The ISM also shows a complex structure consisting of phases at different equilibrium temperatures (for a review, see Draine 2011). The cold phase is a blend of dust, molecules and almost neutral gas below $10^4$ K. The warm and hot phases are mostly gaseous. The warm gas is weakly ionized, with a temperature of $\sim 10^4$ K. The hot gas is highly ionized, with temperatures of about $10^6$ K. These three main phases are not entirely separated from each other. For instance, it is thought that a conductive cooling layer, revealed by O VI, lies between the warm and hot ionized phases (see e.g. Richter 2006).

In the spectra of background sources the ISM produces reddening and absorption lines. High resolution X-ray spectroscopy has become a powerful diagnostic tool for constraining the chemical and physical properties of the ISM. The K-shell transitions of carbon, nitrogen, oxygen, neon, and magnesium, and the L-shell transitions of iron fall in the soft X-ray energy band. The presence of different ionization states constrains the multi-phase temperature structure of the ISM. A summary of the results obtained by X-ray spectroscopy on the ISM in the last decades is given by Pinto et al. (2010).

Briefly, Schattenburg & Canizares (1986) first constrained interstellar oxygen in the X-ray band using the Einstein Observatory, but a thorough study of the ISM was possible only after the launch of the XMM-Newton and Chandra satellites, provided with high-resolution gratings. Absorption structure due to ionized gas and dust was found around the interstellar oxygen K-shell absorption edge in the spectra of several sources (Paerels et al. 2001; de Vries et al. 2003; Juett et al. 2004; Costantini et al. 2005, 2012; de Vries & Costantini 2009; Kaastra et al. 2009; Pinto et al. 2010, 2012a,b).

However, in the last decades, the most important discoveries on the physics of the ISM phases have been obtained with UV, IR, optical, and radio spectroscopy. Dust is usually studied in IR, molecules in radio and IR, while the neutral and warm phases
of the interstellar gas are also probed with UV data (see Ferrière 2001 and references therein). The hot gas is the only ISM phase which is more often studied in X-rays. However, despite the very high resolution and signal-to-noise ratio at long wavelengths, both the chemistry and physics of the interstellar medium are still under debate. Elemental abundances, dust depletion factors and dust chemistry are not yet well determined and thus provide an open and interesting research field. The heavy elements such as oxygen (the most abundant one) and iron are produced in high-mass stars. Molecules and dust compounds are mainly formed in AGB stars and then grow in the diffuse ISM (see e.g. Mattsson & Andersen 2012). Heavy elements directly witness the history of the past stellar evolution. In the last years there have been many attempts to measure the interstellar abundances, but in many cases only lower limits were obtained due to the depletion of the elements from the gaseous phases into dust grains and to strong line saturation at long wavelengths. The dust depletion factors and especially the compounds mixture are not yet well known and thus the total ISM abundances are affected by strong systematic uncertainties. For instance, a significant fraction of the oxygen which is bound in the solid phase is still unknown: silicates and carbonaceous compounds are not abundant enough to cover the amount of depleted oxygen. Ices may solve this problem, but they are hard to detect (for a review about depletion factors in the ISM see Jenkins 2009). Therefore, our work focuses on an alternative method to determine ISM column densities, dust depletion factors, molecular compounds, total abundances (gas + dust), and abundance gradients through X-ray spectroscopy.

In this work we report the detection and modeling of interstellar absorption lines and edges in the high-quality spectra of nine LMXBs: GS 1826–238, GX 9+9, GX 339–4, Aql X–1, SAX J1808.4–3658, Ser X–1, 4U 1254–690, 4U 1636–536, and 4U 1735–444. The observations are taken with the XMM-Newton Reflection Grating Spectrometer (RGS, den Herder et al. 2001), see Table 5.1 for details. These sources are well suited for the analysis of the ISM because of their brightness and column densities \( N_H \sim 1 - 5 \times 10^{25} \text{m}^{-2} \) (see Table 5.2), which are high enough to produce prominent O, Fe, and Ne absorption edges in the soft X-ray energy band. This paper provides a significant extension of the previous work on the ISM in the line-of-sight (LOS) towards GS 1826–238 done by Pinto et al. (2010). We have used updated atomic and molecular database and extended the analysis to several LOS (see Fig. 5.1).

Our analysis focuses on the 7 – 38 Å first order spectra of the RGS detectors. We have not used the EPIC spectra of the observations because they have much lower spectral resolution and we were not interested in determining the source continuum at energies higher than the RGS band. Most of interstellar X-ray features are indeed found in the soft X-ray energy band. We performed the spectral analysis with SPEX\(^1\) version 2.03.03 (Kaastra et al. 1996). We scaled the elemental abundances to the proto-Solar abundances of Lodders & Palme (2009). We use the \( \chi^2 \)-statistic throughout the paper and adopt 1\( \sigma \) errors.

The paper is organized as follows. In Sect. 5.2 we present the data. In Sect. 5.3 we report the relevant spectral features that we analyze. In Sect. 5.4 we describe the

\(^1\text{www.sron.nl/spex} \)
models we use and the results of our analysis. The discussion and the comparison with previous work are given in Sect. 5.5. Conclusions are reported in Sect. 5.6.

5.2 The data

For this work we have used 22 archival spectra of nine sources taken with XMM-Newton (see Fig. 5.1 and Table 5.1). These spectra were taken in periods of high-flux state of the sources and each single spectrum shows high statistics. We have excluded in our analysis additional observations taken during low-flux states. For some sources we have just one good spectrum, while for other ones we obtained up to five high-quality spectra. The spectra taken on the same source have been fitted together in order to increase the statistics, but we have used a different approach between stable and variable sources. When the persistent emission of a certain source was steady and the spectra were perfectly superimposable, we have stacked the spectra according to the procedure described by Kaastra et al. (2011a). Briefly, we have reduced the spectra with the Science Analysis System (SAS) version 11.0, obtained fluxed spectra for RGS 1 and 2 and stacked them with the SPEX task RGS_fluxcombine. We cannot stack the spectra of variable sources because this may introduce spurious features near the interstellar edges. Thus, we simultaneously fit their spectra coupling the parameters of the interstellar absorbers, but adopting a different continuum for each observation. This can be done with the SPEX task sectors.

The LMXBs GS 1826−238, GX 9+9, Ser X−1, 4U 1254−690, and 4U 1636−536 showed little or insignificant spectral variability, thus we could stack their RGS 1 and 2 spectra, which were taken during all the observations, and produce a single final fluxed spectrum for each LMXB (see Figs. 5.2 – 5.4). We adopted a similar approach in Pinto et al. (2010) for GS 1826−238. There we filtered out the bursting emission from the spectra but also reported that it was negligible compared to the persistent emission. Therefore we do not remove the periods of bursts in any of our data.

For Aql X−1, SAX J1808.4−3658, and 4U 1735−444 we have only found one very good spectrum. Their other observations available in the archive have either too short exposure or much lower flux in such a way that they do not significantly improve the statistics. For each of these sources we simply fit the RGS 1 and 2 count spectra simultaneously. The LMXB GX 339−4 is an exception. Its spectral continuum and slope strongly vary, but the three observations with IDs 0148 and 0605 have superimposable spectra, as well as the remaining two observations (IDs 0204). Therefore we split the spectra in these two groups and stack them producing two final fluxed spectra with comparable statistics. In Figs. 5.2 – 5.4 with show the Ne, Fe, and O absorption edges of the GX 339−4 fluxed spectrum obtained by stacking the group of observations with ID 0204.

In Table 5.1 we report the RGS exposure times and identification number for each observation. We also provide the Galactic coordinates, distance d and hydrogen column density $N_H$ for each source. Most of the distances have been taken from Galloway et al. (2008), which estimated them through the luminosity peak during the LMXB burst. The $N_H$ ranges refer to the spread between the values measured by the Le-
5.3 Spectral features

In Figs. 5.2 – 5.4 we show the neutral absorption edges of neon, iron, and oxygen for the nine LMXBs, which are the strongest spectral features. SAX J1808.4–3658 also shows a prominent N\textsc{i} 1s–2p edge at 31.3 Å, but most of the sources have weak nitrogen and magnesium edges, which means that the Mg and N abundances are not well constrained. The Ne\textsc{i} edge (see 14.3 Å in Fig. 5.2) is shallower than those of Fe and O, but it is interesting for the presence of additional absorption lines due to mildly ionized Ne\textsc{ii-iii} and heavily ionized Ne\textsc{ix} gas. For a few sources we are even able to detect a weak Ne\textsc{viii} line at about 13.7 Å. The iron L2 and L3 edges are located at 17.15 and 17.5 Å (see Fig. 5.3). The sources show clear differences in the depth of these edges. We also provide the position of the O\textsc{vii} β (1s–3p) and O\textsc{viii} α (1s–2p) absorption lines at 18.6 and 19.0 Å, respectively. These two lines also trace the hot ionized gas. Fig. 5.4 shows the most interesting part of the spectrum: the oxygen K edge. The O\textsc{i} 1s–2p line at about 23.5 Å is the strongest ISM spectral feature, the neutral oxygen...
Table 5.1: XMM-Newton/RGS observations used in this paper.

<table>
<thead>
<tr>
<th>Source</th>
<th>ID (a)</th>
<th>Length (ks) (b)</th>
<th>l, b (c)</th>
<th>d (kpc) (d)</th>
<th>$N_H$ (10^{25} m^{-2}) (e)</th>
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<td>0405510301</td>
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<td>0303250201</td>
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<td>7.5 (b)</td>
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<td>2.77 (f)</td>
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<td></td>
<td>0084020501</td>
<td>21.7</td>
<td>36.1, 4.8</td>
<td>7.7 (f)</td>
<td>4.0–4.7</td>
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<td>0084020601</td>
<td>21.8</td>
<td></td>
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</tr>
</tbody>
</table>

(a, b) Identification number and duration of the observation. (c, d, e) Source Galactic coordinates in degrees, distance from the Sun, and hydrogen column density (see Kalberla et al. 2005 and Dickey & Lockman 1990). (f) Distance estimates are taken from Galloway et al. (2008). (g) For GX 339-4 we adopt the distance as suggested by Zdziarski et al. (2004). (h) The distance for GX 9+9 is the mean value between those ones provided by Christian & Swank (1997) and Zdziarski et al. (2004).
is also responsible for the jump in spectrum between 22.5 and 23.2 Å. Additional but not less important 1s–2p absorption lines are produced by O II (23.35 Å), O III (23.1 Å), O VII (21.6 Å), and occasionally O VI (22.0 Å). Dust oxygen compounds affect mainly the spectral curvature between 22.7 – 23.0 Å (see e.g. Pinto et al. 2010, and references therein). An easy way to check for strong amounts of dust is to compare the depth of the edge with that of the line. Dust usually is responsible for a deep edge, while the gas also provides strong lines. For instance, in Ser X-1 the O K edge is deeper than the 1s–2p line, while in SAX J1808.4–3658 the absorption line is clearly deeper than the edge. This means that along the LOS towards Ser X-1 the amount of oxygen found in dust compounds is expected to be larger. We will confirm this in Sect. 5.5. Dust is also expected to provide most of iron (see e.g. Jenkins 2009), which means that the bulk of the absorption between 17–17.5 Å is produced by iron dust compounds (see also Costantini et al. 2012). Dust is also responsible for most of the magnesium edge at about 9.5 Å.

5.4 Spectral modeling of the ISM

The advantage of using LMXBs for the analysis of the ISM lies in their high-statistics and simple spectrum. All the sources in our sample provided us with well exposed spectra, which are easy to model by adopting a simple continuum. In most of the cases one power-law (PL) continuum gave an acceptable and quickly-converging fit. When a single PL did not provide a good fit then we were able to obtain an acceptable fit by simply adding another PL. The continuum of LMXBs usually originates from their accretion disk and corona in the form of blackbody and comptonized emission, respectively. However, we are using only the soft part of the X-ray spectrum which is relevant for the ISM absorption and is not broad enough to provide accurate constraints on the X-ray emission components. Moreover, this work does not focus on the nature of the continuum intrinsic to the sources. Thus, we prefer to use PL components rather than physical ones like blackbody (BB) or comptonization (COMT). In principle the choice of the continuum component may affect the estimate of the hydrogen column density, while the other ionic columns are well constrained as they are estimated through narrow absorption lines which do not depend on the continuum. Thus, we also tested both PL and a combination of BB / COMT in modeling our RGS spectra (bb and comt models in SPEX). The best fit values of $N_H$ were consistent within the errors, which validates our choice of a simple PL continuum.

We have built an empirical model for the ISM similar to that one successfully used by Pinto et al. (2012a) but with a few useful changes. Essentially, they used three components modeled with the slab model of SPEX to fit the three main phases of the interstellar gas. The slab model gives the transmission through a layer of gas with arbitrary ionic column densities. Here we also use two slab components to model the warm and hot phases of the ISM, but we prefer to model the cold neutral gas with the hot component in SPEX. The hot model calculates the transmission of a collisionally-ionized equilibrium plasma. For a given temperature and set of abundances, the model calculates the ionization balance and then determines all the ionic column densities by
Figure 5.2: Data and best-fitting models: the Ne K edge.
Figure 5.3: Data and best-fitting models: the Fe L2 and L3 edge.
Figure 5.4: Data and best-fitting models: the O K edge.
5.4 Spectral modeling of the ISM

to the prescribed total hydrogen column density. At low temperatures this model mimics very well the neutral interstellar gas (see SPEX manual and Kaastra et al. 2009). Free parameters in the hot model are the hydrogen column density \(N_H\), the temperature \(T\), the velocity dispersion \(\sigma\), the systematic velocity \(v\), and the abundances. However, in X-rays the spectral resolution is not high enough to constrain the velocities with sufficient accuracy, thus we assume that the interstellar gas is at rest. We also assume a temperature of 0.5 eV (about 5800 K), the lowest value available in the SPEX hot model, because in this way the gas is mostly neutral. In X-rays with the current satellites it is not possible to resolve the narrow lines of the interstellar medium. A spectral fit can easily provide a wrong value of velocity dispersion \(\sigma\), and consequently of column density because they are degenerate. Therefore it is more appropriate adopting a physically reasonable value for the \(\sigma\), and just fitting the column density of each ion. We adopt a nominal value of 10 km s\(^{-1}\) for the velocity dispersion of the cold (O I) and warm (O II-V) gas components, which is similar to that found by Pinto et al. (2012a) using a higher-resolution UV spectrum. For the hot gas (O VI and higher ionization states) we adopt \(\sigma = 100 \text{ km s}^{-1}\), which is an average value between those suggested in the literature (see for instance the work by Yao & Wang 2005 and Yao et al. 2009a on high-resolution Chandra X-ray spectra of several LMXBs). We took into account absorption by interstellar dust with the SPEX amol component. The amol model calculates the transmission of various molecules, for details see Pinto et al. (2010), Costantini et al. (2012) and the SPEX manual. The model currently takes into account the modified edge and line structure around the O and Si K-edge, and the Fe K / L-edges, using measured cross sections of various compounds taken from the literature. Relevant and abundant silicates, ices and organic molecules are present in the our database. In fitting the molecular models we limit the range of column densities to physical values. For instance, we took care that the column density of each weakly-abundant element did not exceed the proto-Solar value predicted by the best-fitting \(N_H\). This is important especially for Ca and Al (contained respectively in andradite and hercinite), whose abundances are much lower than oxygen.

5.4.1 Results

The results of our best fitting model obtained on the X-ray sources are shown in Table 5.2 and plotted in Figs. 5.2–5.4. The model fits very well both the absorption edges and lines. We show the absolute abundances and hydrogen column density for the cold gas, the column densities for all ions and molecules that we were able to detect. In the cases of no detection we report the 2\(\sigma\) upper limits. We also report the formula for each compound and the total amount of iron and oxygen found in dust. We will discuss the results in Sect. 5.5. Briefly, we have found a general agreement in the spectra of the different sources. Ions like O V-VI and molecular compounds like hematite (Fe\(_2\)O\(_3\)), and CO are hard to detect. Instead, O VII-VIII, H\(_2\)O ices, and compounds of Ca (andradite), and Al (Hercinite) are detected along any LOS. The cold neutral gas provides on average O I \(\sim 1 – 3 \times 10^{22} \text{ m}^{-2}\), which means that most oxygen is found in the neutral phase. We have summed all the contributions to the molecular oxygen as well as all the ionic column densities of the mildly ionized (O II-V) and heavily ionized
(O\textsubscript{VI}-\textsubscript{VIII}) gas, and compare them in Table 5.3. As we have mentioned above, most of the oxygen is provided by the neutral gas phase. Dust also seems to be ubiquitous. The warm and hot ionized gas phases generally contribute less to oxygen, but there are some cases in which they constitute significant portions of the total column density.

### 5.4.2 Limitations

There are some factors that may limit and affect the uniqueness of our best-fitting models. First of all, the features produced by molecules in a certain absorption edge are similar and degenerate. Near the Fe L-edge the RGS absorption lines blend and may not give unique solutions. Chandra spectra are provided with higher resolution, but they give accurate results only for a few sources even brighter than ours. Therefore, in our standard modeling we have simultaneously fitted all the molecules and all the absorption edges and lines in order to obtain the best-fitting mixture and to break as much as possible the degeneracy. Unfortunately, for some compounds, such as magnetite and pyroxene, we only have the transmission near the oxygen edge, while for the other edges we simply use the pure atomic cross-section without absorption lines (for details consult the amol model in the SPEX manual). As we already mentioned, we performed additional fits with different combinations of molecules by excluding some of them. However, the total amount of oxygen and iron in dust did not strongly depend on the chosen dust mixture. Therefore, their depletion factors are not highly effected, while the detailed chemical structure may be.

On another hand, the molecular database is not complete. We have tested all the molecules available in the SPEX database, which are about 40 (carbon oxides, ices, iron and magnesium silicates, and more complex molecules). Although these compounds are among the most abundant in the ISM, we could still miss important contribution from other species like forsterite (Mg\textsubscript{2}SiO\textsubscript{4}, see e.g. Jones 2000). For instance, we may have overestimated the presence of water ice, as in the diffuse interstellar medium its amount should be small (Jenkins 2009). As mentioned in Sect. 5.4 concerning the spectral fitting, we have limited the column densities of the molecules responsible for Al (hercinite) and Ca (andradite). If the O/Ca and O/Al ratios in the ISM molecules are higher than those of our sample, then the amount of oxygen in silicates and other oxides can increase at the expense of ices. Moreover, there is some degeneracy due to the similarity of the absorption profiles of ice and pyroxene (see e.g. Costantini et al. 2012), which would require spectra with higher signal-to-noise ratios.

The results obtained on the various absorption edges have different weights. The oxygen edge is the deepest and the column densities of oxygen compounds are constrained better than for iron. The Mg edge is very weak for hydrogen column densities like those of our sources and the estimates of magnesium abundances and depletion factors are much more uncertain. This does not apply to neon as it is supposed to be only in a gaseous phase. This work mostly focuses on measurements of interstellar oxygen, iron, and neon column densities. A deep analysis of magnesium and silicon would require the use of both the XMM-Newton RGS and the Chandra HETG gratings (which have higher effective area and resolution than RGS at short wavelength) in combination with sources with higher hydrogen column densities.
Table 5.2: RGS fits with the complete ISM model. The dust and the three gas phases are represented by the four main blocks.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4U1245-690</th>
<th>4U 1636-536</th>
<th>4U 1735-444</th>
<th>4G X-1</th>
<th>GS 1826-238</th>
<th>G3X 339-4</th>
<th>G9 X+9</th>
<th>SAX J1808.4-3638</th>
<th>Ser X-1</th>
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</thead>
<tbody>
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<td>$N_H (10^{21} \text{ m}^{-2})$</td>
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<td>3.58 ± 0.07</td>
<td>3.28 ± 0.01</td>
<td>5.21 ± 0.03</td>
<td>4.14 ± 0.06</td>
<td>5.08 ± 0.01</td>
<td>2.15 ± 0.05</td>
<td>1.40 ± 0.01</td>
<td>4.98 ± 0.16</td>
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<td>O/H</td>
<td>0.92 ± 0.02</td>
<td>0.840 ± 0.013</td>
<td>0.93 ± 0.02</td>
<td>0.878 ± 0.007</td>
<td>0.915 ± 0.009</td>
<td>1.061 ± 0.004</td>
<td>0.99 ± 0.02</td>
<td>0.913 ± 0.035</td>
<td>0.90 ± 0.02</td>
</tr>
<tr>
<td>Ne/H</td>
<td>0.91 ± 0.03</td>
<td>1.315 ± 0.015</td>
<td>1.00 ± 0.05</td>
<td>0.951 ± 0.025</td>
<td>1.23 ± 0.04</td>
<td>1.05 ± 0.05</td>
<td>1.35 ± 0.07</td>
<td>1.37 ± 0.05</td>
<td>1.20 ± 0.05</td>
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<tr>
<td>Mg/H</td>
<td>1.7 ± 0.3</td>
<td>&lt; 0.20</td>
<td>2.0 ± 0.3</td>
<td>1.00 ± 0.13</td>
<td>1.41 ± 0.12</td>
<td>1.17 ± 0.05</td>
<td>0.41 ± 0.25</td>
<td>&lt; 0.16</td>
<td>0.89 ± 0.09</td>
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<tr>
<td>Fe/H</td>
<td>0.16 ± 0.05</td>
<td>0.176 ± 0.017</td>
<td>0.25 ± 0.06</td>
<td>0.113 ± 0.015</td>
<td>0.234 ± 0.017</td>
<td>0.365 ± 0.006</td>
<td>0.19 ± 0.03</td>
<td>&lt; 0.02</td>
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<td>O/H</td>
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<td>Mg/H</td>
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<td>Fe/H</td>
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<td>0.234 ± 0.017</td>
<td>0.365 ± 0.006</td>
<td>0.19 ± 0.03</td>
<td>&lt; 0.02</td>
<td>0.59 ± 0.03</td>
</tr>
</tbody>
</table>

- (a) Abundances ratios are in the linear proto-Solar abundance units of Lodders & Palme (2009).
- (b) Ionic and molecular column densities are in units of $10^{21} \text{ m}^{-2}$ (see also Sect. 5.4).
Our estimates of column densities and abundances provide interstellar properties as integrated along the LOS and on a large scale. This is reasonable for the diffuse gas, which is almost uniformly distributed between 3–15 kpc from the Galactic Center and whose warm phase may reach a few kpc height from the Galactic place (see e.g. Ferrière 2001). This scale-height is indeed comparable to the average altitude of our sources (see Table 5.1). However, this assumption may not be correct for dust and molecules, which follow the Galactic spirals and are usually found at lower altitudes. This means that dust sampling towards our targets may be closer to the Sun rather than in the middle of the path. In the cold phase, iron and magnesium are strongly depleted into dust. Therefore, the average location of the Fe and Mg absorbers can be found at shorter distances than those referring to oxygen and neon. However, in Sect. 5.5.2 we will show that along our low-latitude LOS the different scale-heights of gas and dust will not affect the results.

5.5 Discussion

Our analysis shows that the ISM has a multi-phase structure characterized by cold neutral gas (and dust), mildly ionized gas and heavily ionized gas. This complex structure is found towards any of the studied sources (see Table 5.2) and is consistent with our previous work (see e.g. Kaastra et al. 2009; Pinto et al. 2010, 2012a; Costantini et al. 2012). Signatures of dust are always present with main contributions by ices and silicates. The oxygen edge and lines provide the most accurate results due to their large depth, but the results are even more robust because of the simultaneous modeling of all the absorption edges. This was crucial especially for fitting dust and molecules which affect both O, Fe, and Mg edges. An interesting and simple check of different amounts of oxygen in dust is provided by the comparison of the O K edge in Fig. 5.4. As we anticipated in Sect. 5.3, the O I 1s–2p absorption line is deeper than the oxygen edge for SAX J1808.4−3658, while for Ser X−1 and GX 339−4 they are comparable. We attribute this to oxygen depleted from the gas phase into dust grains, which is confirmed by the measurement of a larger amount of oxygen in solids in the LOS towards the two latter sources (see Table 5.2).

5.5.1 The nature of the gas phases

In our standard model we have used a collisionally-ionized model in SPEX because at low temperatures this mimics well the cold interstellar gas. However, at these temperatures photo-ionization could also provide a significant contribution. Therefore, we tried an alternative model in which a photo-ionized component (xabs in SPEX) substitutes the cold collisionally-ionized hot component. The fits are equivalent, the gas is almost neutral with a very low ionization parameter $\xi$. Abundances and $\chi^2$ are consistent with our standard model. The main difference is that the fit with the photo-ionized model takes more time to converge and the absolute abundances, i.e. relative to hydrogen, have larger uncertainties (see also Pinto et al. 2012a). Therefore, we prefer to keep our standard model even if photo-ionization is not ruled out.
5.5 Discussion

We have also considered an alternative, physical model for the warm mildly-ionized gas that produces most of the O\textsubscript{II}-IV and Ne\textsubscript{II}-III absorption lines. Instead of a slab absorber we have tested a photo-ionized xabs component, which was successfully used by Pinto et al. (2012a) in the deep UV and X-ray spectra of the AGN Mrk 509. The fit was bad because a single photo-ionized component is not able to fit all the large column densities as measured by our empirical standard model and shown in Table 5.2. We need a low-ionization component which provides the bulk of O\textsubscript{II} and Ne\textsubscript{II} together with an intermediate-ionization component for the other ions. Interestingly, a good fit is obtained when using the same abundance pattern as provided by the cold neutral gas, while proto-Solar abundances give a bad fit. However, a thorough study of the warm gas requires longer exposures and complementary UV data, which is beyond the scope of this paper.

The heavily ionized gas is usually found to be in collisional equilibrium. However, it is thought that this hot gas in the Galaxy is not characterized by a single phase, but it is constituted of two main phases. Most O\textsubscript{VII-VIII} should arise from a very hot ($\sim 2 \times 10^6$ K) collisionally-ionized phase, while the bulk of O\textsubscript{VI} is thought to be embedded in a cooling phase with temperatures $1 – 5 \times 10^5$ K (see e.g. Richter 2006). We have tested both single-phase and two-phase models by substituting the slab component responsible for the O\textsubscript{VI-VIII} absorption with one and two collisionally-ionized hot components in SPEX. The fits are comparable due to the weakness of their absorption lines. We would need UV O\textsubscript{VI} data in order to put strong constraints, but most of our targets have not been observed with COS/HST or FUSE. However, Table 5.2 shows a spread larger than 10 in the O\textsubscript{VII} / O\textsubscript{VIII} column ratio, which for a single gas component would provide a very large scatter in temperature between the nine LOS (from 1.2 to 2.6 million K). We think that combinations of two stable, but different hot (cooling and coronal) phases is a more likely description.

5.5.2 Is the ISM chemically homogeneous?

On small scales the ISM is not expected to be highly homogeneous because there are significant physical and chemical differences between the interstellar environments like H\textsubscript{II} regions, PNe nebulae, dark clouds, etc. However, the diffuse medium in our Galaxy may be homogeneous on large scales. Some chemical and physical properties may be possibly consistent when comparing distant regions which underwent a similar evolution. This is possible for dust as most of it is expected to grow in the ISM rather than in stars (see e.g. Mattsson & Andersen 2012). It is thus worth to compare its chemical properties as integrated along the different LOS. First of all, we notice that the molecular composition is similar in any direction. Aluminates and calcium silicates are found to provide most of Al and Ca, which are indeed expected to be highly depleted into dust. Even more interesting is the detection of water ice which was suggested by Jenkins (2009) as a possible principal resource of oxygen in dust and a solution to the problem of oxygen depletion. The same applies to metallic iron. We remark that the amount of water ice as measured by us may be overestimated due to the small sample of molecules in the current database (see Sect. 5.4.2). Cross-sections of additional compounds are currently being measured and may provide more accurate results. To
understand the role of dust, we have summed all the contributions to oxygen from solids and molecules and compared it with the hydrogen column density that we have obtained in our best fits (see Fig. 5.5). We show the trends of both the total column density of dusty oxygen and its fraction with respect to the total amount of neutral oxygen (gas + dust) as function of the $N_{\text{H}}$. The oxygen dust column correlates well with the hydrogen column density (slope $= (1.4 \pm 0.1) \times 10^{-4}$) and the fraction of oxygen bound in dust is constant ($18 \pm 3\%$) along any LOS. These results suggest that on average the cold ISM phase is chemically homogeneous. We notice that the total amount of oxygen in dust is solidly measured as it does not strongly depend on the dust mixture. For instance, we tested different molecular combinations by removing some of the main compounds from the fit, but in the end the sum of all the oxygen molecular column densities provide the same results in the fits. The same applies for iron, whose dust fraction does not depend on the $N_{\text{H}}$ and the LOS, but it has a larger uncertainty and spreads between 70–90\%. This occurs because the iron L edge is shallower than the oxygen K edge. As we mentioned in Sect. 5.4.2, the scale-height of the interstellar dust is smaller than for the gas, thus, due to the altitudes of the targets, the dust is expected at shorter distances from the Sun. This means that the analysis of the dust in these different LOS probes properties of the ISM as measured on a large scale, but probably smaller than with the gas. As additional check we have computed the dust-to-gas ratio for our sources as the ratio between the total amount of oxygen in dust and the hydrogen column density. The dust-to-gas ratio is constant (slope $= -0.027 \pm 0.034$) at any value of Galactic latitude as shown in Fig. 5.6. This result and the trend seen in Fig. 5.5 suggest that the distribution of the dust should not deviate from the gas. This may be due to the low latitudes of our sources, which was also one of the reasons for us to choose these targets as representatives of the Galactic (inner) disk.

5.5.3 ISM column densities

Our empirical model provides us with estimates of column densities for several molecular and ionic species (see Table 5.2). In some cases we could only obtain upper limits, but we prefer to show them as they may be useful for future work. In order to further check the robustness of our model we compare our column density estimates with those found in the literature. In most cases our best-fit values of $N_{\text{H}}$ agree with those measured at longer wavelength (see Table 5.1). On average our values are slightly higher that the 21 cm H I estimates probably because the curvature as measured in the X-ray above 25 Å takes into account the contributions from H I and H$_2$. Our values are consistent with other papers (see e.g. Xiang et al. 2005; Caballero-García et al. 2009; Bhattacharyya & Strohmayer 2007; Patruno et al. 2009). Our column density estimate for GS 1826–238 agrees with what we found with a different model in Pinto et al. (2010), i.e. $N_{\text{H}} = 4.14 \pm 0.07 \times 10^{25}$ m$^{-2}$. All the neutral column densities that we have measured for 4U 1636–536, 4U 1735-444, GX 339–4, GX 9+9, and Ser X-1 are consistent with Juett et al. (2004, 2006). We found a disagreement between our average values of O III/O I and O III/O I column density ratios, $\sim 0.06$ and $\sim 0.01$ respectively, with those obtained by Juett et al. (2004) of about 0.1. This may be due to the fact that their model does not take into account any contribution by dust or molecules near 23 Å and thus may over-
Figure 5.5: Amount of O\textsubscript{I} in dust and its fraction with respect to the total neutral oxygen (gas + dust) versus the hydrogen column density.

Figure 5.6: Ratio between the Amount of O\textsubscript{I} in dust and the hydrogen column density versus the absolute value of the Galactic latitude.
estimate the amount of ionized oxygen. Our O\textsuperscript{VII} column densities are significantly larger than those estimated by Miller et al. (2004) for GX 339–4 probably because they have adopted a much larger velocity dispersion or because of saturation which usually affects absorption lines with $\sigma > 60$ km s$^{-1}$ (see e.g. Yao & Wang 2005). We point out that many of the high-resolution X-ray (RGS) spectra of these sources have been analyzed for the first time by us.

5.5.4 ISM abundances

We have also estimated the total abundances of O, Ne, Mg, and Fe for the cold phase in units of Lodders & Palme (2009) by summing, for each element, the contributions from neutral gas, dust, and molecules (see Table 5.4). In most cases all the elements appear to be over-abundant with respect to the proto-Solar values. This is expected as all LOS cross inner Galactic regions where the abundances are higher. It is very difficult to estimate the location of the absorbing medium for several reasons. At first, we integrate over the LOS and thus our abundances have to be considered as large-scale properties of the ISM. Moreover, the ISM mass-density distribution within the Galaxy is not well known and the LMXB distances are affected by a large uncertainty which will dominate the error on the ISM absorber location. Therefore, we adopt half of the distance to each LMXB as a first-order, average-distance indicator. This means that the Galactocentric radius $R_G$ of each ISM absorber will be defined as the distance from the Galactic Center (hereafter GC) to the mean point of the segment which connects the Sun to each target. We show the abundance trends for O, Ne, Mg, and Fe with respect to $R_G$ (in kpc) in Fig. 5.7. These trends were fitted with a linear function and we obtained the following abundance gradients:

$$12 + \log (O/H) = (8.98 \pm 0.03) - (0.023 \pm 0.006) \times R_G,$$
$$12 + \log (Fe/H) = (7.75 \pm 0.13) - (0.033 \pm 0.023) \times R_G,$$
$$12 + \log (Ne/H) = (8.33 \pm 0.03) - (0.031 \pm 0.006) \times R_G,$$
$$12 + \log (Mg/H) = (7.87 \pm 0.10) - (0.028 \pm 0.020) \times R_G.$$

The plots show that only the oxygen abundance is clearly anti-correlated with the distance from the GC. Neon also shows a gradient but with a large scatter probably due to contribution intrinsic to the sources (see e.g. Juett & Chakrabarty 2003 and Madej et al. 2010). However, the linear fits show negative gradients for all the abundances which is consistent with the fact that stellar evolution proceeds faster in the Galactic inner regions. Interestingly, our abundance gradients agree with those estimated with different methods and in different wavelength regimes (Maciel & Quireza 1999; Rolleston et al. 2000; Esteban et al. 2005; Pedicelli et al. 2009). On average our values are slightly smaller than those found in the literature. An explanation may be that we overestimated the distance of the absorbers by a (small) systematic factor. In fact, the LMXBs are not exactly in the Galactic Plane, but are above or below by some hundreds parsec. This means that the distance of each ISM absorber, as projected on the Galactic plane, should be smaller than what we have adopted. The altitudes of the LMXBs also affect the abundance estimates because of the (negative) vertical metallicity gradient.
5.5 Discussion

(see e.g. Pedicelli et al. 2009). The slopes of the radial and vertical gradients are similar (we have compared their effects in Pinto et al. 2012a). The sources have low latitudes (see Table 5.1), on average we obtained $\bar{b} \sim 6.1^o$, which implies that the radial abundance variations are about 10 times larger than the vertical ones. This explains why ignoring the vertical gradient may only marginally affect our results. We may have underestimated the Mg and Fe abundance gradients also because in the cold phase these elements are locked up into dust. In fact, as reported in Sect. 5.4.2, dust could be found at distances shorter than the gas along our LOS. This means that the average distances of the Fe and Mg absorbers may be smaller and the gradients higher than those estimated. However, once taken all this into account, our estimates of abundance gradients agree even better with the literature.

We can also predict the local proto-Solar interstellar abundances and check if they agree with those found in the Solar system. According to the equation above, we calculate that at the Galactocentric radius of the Sun, which is $\sim 8.0$ kpc (see e.g. Malkin 2012), the predicted proto-Solar abundances are

\[
\begin{align*}
12 + \log (\text{O}/\text{H})_\odot &= (8.80 \pm 0.05), \\
12 + \log (\text{Fe}/\text{H})_\odot &= (7.48 \pm 0.23), \\
12 + \log (\text{Ne}/\text{H})_\odot &= (8.08 \pm 0.05), \\
12 + \log (\text{Mg}/\text{H})_\odot &= (7.66 \pm 0.19).
\end{align*}
\]

These values agree very well with the abundances in the Solar System as measured by Lodders & Palme (2009) $[\text{O}/\text{H}]= 8.76$, $[\text{Fe}/\text{H}]= 7.54$, $[\text{Ne}/\text{H}]= 7.95$, $[\text{Mg}/\text{H}]= 7.62$, and further validate our method. Interestingly, the interstellar oxygen abundance, as measured by previous work, is always lower than the abundance estimates for the Solar System, OB stars, H II regions, planetary nebulae, Cepheids, and Sun-like stars (see e.g. Stasińska et al. 2012 and Nieva & Przybilla 2012). Instead, our measurements and predictions agree very well with the abundances of these stellar indicators, which confirms that the local Galaxy is chemically homogeneous (see also Stasińska et al. 2012).

As clearly seen in Fig. 5.7, our work is optimal to probe ISM abundances within 4–8 kpc from the GC, but this range could be easily extended by using more sources. This may be an interesting proxy for a future work extended to more LOS and background source types like LMXBs, novae and AGN (especially Blazars, which do not show significant intrinsic features).
### Table 5.3: Oxygen diagnostics: percentage contributions from the different phases and total column density.

<table>
<thead>
<tr>
<th>Phases</th>
<th>4U1254–69</th>
<th>4U 1636–54</th>
<th>4U 1735–44</th>
<th>Aql X–1</th>
<th>GS 1826–24</th>
<th>GX 339–4</th>
<th>GX 9+9</th>
<th>SAX J1808.4</th>
<th>Ser X-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>O I (dust)</td>
<td>13</td>
<td>19</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>13</td>
<td>17</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>O I (gas)</td>
<td>71</td>
<td>70</td>
<td>66</td>
<td>84</td>
<td>78</td>
<td>72</td>
<td>77</td>
<td>57</td>
<td>73</td>
</tr>
<tr>
<td>O II–V</td>
<td>5</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>O VI–VIII</td>
<td>11</td>
<td>2</td>
<td>17</td>
<td>1</td>
<td>11</td>
<td>1</td>
<td>17</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>O TOT</td>
<td>2.10</td>
<td>2.59</td>
<td>2.79</td>
<td>3.31</td>
<td>2.93</td>
<td>4.53</td>
<td>1.66</td>
<td>1.37</td>
<td>3.72</td>
</tr>
</tbody>
</table>

(a) Column ratios are expressed in percentage. (b) Oxygen total column densities are in linear units of \((10^{22} \text{ m}^{-2})\).

### Table 5.4: Total abundances of the cold neutral phase (gas + dust).

<table>
<thead>
<tr>
<th>Species</th>
<th>4U1254–69</th>
<th>4U 1636–54</th>
<th>4U 1735–44</th>
<th>Aql X–1</th>
<th>GS 1826–24</th>
<th>GX 339–4</th>
<th>GX 9+9</th>
<th>SAX J1808.4</th>
<th>Ser X-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>O/H</td>
<td>1.12 ± 0.04</td>
<td>1.16 ± 0.06</td>
<td>1.14 ± 0.06</td>
<td>1.06 ± 0.05</td>
<td>1.14 ± 0.06</td>
<td>1.30 ± 0.03</td>
<td>1.27 ± 0.06</td>
<td>1.09 ± 0.07</td>
<td>1.13 ± 0.06</td>
</tr>
<tr>
<td>Ne/H</td>
<td>0.91 ± 0.03</td>
<td>1.315 ± 0.045</td>
<td>1.00 ± 0.05</td>
<td>0.951 ± 0.025</td>
<td>1.23 ± 0.04</td>
<td>1.05 ± 0.05</td>
<td>1.35 ± 0.07</td>
<td>1.37 ± 0.05</td>
<td>1.20 ± 0.05</td>
</tr>
<tr>
<td>Mg/H</td>
<td>1.7 ± 0.3</td>
<td>0.95 ± 0.10</td>
<td>2.1 ± 0.3</td>
<td>1.00 ± 0.13</td>
<td>1.47 ± 0.15</td>
<td>1.39 ± 0.07</td>
<td>0.8 ± 0.4</td>
<td>&lt;0.3 (b)</td>
<td>1.75 ± 0.26</td>
</tr>
<tr>
<td>Fe/H</td>
<td>0.77 ± 0.35</td>
<td>1.26 ± 0.19</td>
<td>0.7 ± 0.3</td>
<td>1.11 ± 0.11</td>
<td>1.34 ± 0.15</td>
<td>1.21 ± 0.11</td>
<td>1.13 ± 0.17</td>
<td>0.77 ± 0.21</td>
<td>1.00 ± 0.15</td>
</tr>
</tbody>
</table>

(a) Abundances ratios are in the linear proto-Solar abundance units of Lodders & Palme (2009).  
(b) For magnesium abundance we obtain only an upper limit.
5.6 Conclusion

We have presented a detailed treatment of the interstellar medium towards the nine LMXBs: GS 1826–238, GX 9+9, GX 339–4, Aql X–1, SAX J1808.4–3658, Ser X–1, 4U 1254–690, 4U 1636–536, and 4U 1735–444. These bright X-ray sources are spread over about 100 degrees in longitude and are located near the Galactic plane, which makes them a very good workbench for a study focused on the ISM in the Galactic disk.

We probed the ISM dust composition, total abundances, and abundance gradients. We have shown that along these LOS the ISM is composed of a complex mixture of a multi-phase gas, dust, and molecules. The analysis of all ionic species of oxygen showed that the gas is mostly neutral. The column densities of the neutral gas species are in agreement with those found in the literature. The column densities that we estimated for the mildly ionized gas are generally lower because previous work did not take into account that a significant part of the ISM transmission may be provided by dust. Oxygen in solids is mostly provided by ices and silicates. About 15–20% and 70–90% of the total amount of neutral oxygen and iron, respectively, is found in dust. This result provides a solution to the problem recently raised on the oxygen depletion and total abundance in the interstellar medium. Interestingly, the dust contribution and the compounds mixture seem to be consistent along all the lines-of-sight (LOS). The ratios between the different ionization states are also similar between the LOS. This suggests that on a large scale the ISM is chemically homogeneous. Finally, using our X-ray data we confirm the abundance gradients in the Galaxy and the local proto-Solar abundances as derived at longer wavelengths. Through the comparison between our estimates of oxygen abundance and those obtained by other work on nearby young stars and other indicators such as H II regions and planetary nebulae, we also confirm that the local Galaxy is chemically homogeneous. This work shows that X-ray spectroscopy is a very powerful method to probe the ISM.

Acknowledgements

This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). SRON is supported financially by NWO, the Netherlands Organization for Scientific Research. We are grateful to Jean in’t Zand and Frank Verbunt for the useful discussion about the physics and distances of the low-mass X-ray binaries.
Figure 5.7: Abundance gradients on a logarithmic scale. The blue dotted lines show the proto-Solar values.
Chapter 6

Conclusions & Prospects

The interstellar medium (ISM) is the ideal partner of the stars in the evolutionary cycle of the Galaxy. Heavy elements from carbon to uranium are produced by stellar evolution and are released in the surrounding ISM. Part of the interstellar (IS) matter is used to give birth to new stars. Abundances of heavy elements in the ISM are therefore important to probe the past stellar evolution. However, the IS abundances are still to be accurately determined, even for the most abundant metals such as Fe and O. Strong systematic uncertainties are due to the unknown detailed chemical composition of these elements which are significantly depleted in dust. Therefore this thesis aims to provide a successful method to measure the amounts of metals and dust in the ISM through observations of their absorption lines in X-ray spectra of background sources.

6.1 Structure and homogeneity of the diffuse ISM

In the previous chapter we have shown that X-ray absorption spectroscopy is a powerful tool to investigate the ISM. Through the study of its absorption lines in the X-ray spectra of background sources like active galactic nuclei (AGN) and X-ray binaries it was indeed possible to measure column densities for several molecular, atomic, and ionized gas species for heavy elements like C, N, O, Ne, Mg, Si, and Fe. Once we took into account all the contributions from dust and gas, we have accurately determined the total abundances for the cold interstellar phase. We also determined abundance gradients in the Galaxy for interstellar O, Ne, Mg, and Fe. They were consistent with abundances gradients estimated with different methods (see e.g. Chapter 2, 4, and 5). Briefly, all the abundances increase towards the center of the Galaxy confirming that stellar evolution proceeds faster in the inner regions of the Galaxy. However, the gradients generally differ between the various elements, which suggests that the ratios
between the contributions to ISM metal enrichment provided by giant evolved stars and supernovae vary within the Galaxy. A thorough dedicated study to this field is required in order to provide more accurate estimates. However, we have confirmed that along any line-of-sight (LOS) the diffuse ISM is composed of a complex mixture of a multi-phase gas and dust. The analysis of all ionic species of oxygen showed that the gas is mostly neutral. Oxygen in solids is mostly provided by ices and silicates. About 15–20% and 70–90% of the total amount of neutral oxygen and iron, respectively, is found in dust. This result provides a solution to the problem recently raised on the oxygen depletion and total abundance in the ISM. Interestingly, the dust contribution and the compounds mixture seem to be consistent along any LOS. The ratios between the different ionization states do not strongly vary within the Galactic disk. This suggests that on a large scale the ISM is chemically homogeneous. Finally, through the comparison between our estimates of IS oxygen abundance and those obtained by other work on nearby young stars and other indicators such as H II regions and planetary nebulae, we also confirm that the local Galaxy is chemically homogeneous.

6.2 Distinguishing clouds in the ISM, CGM, and IGM

The multiwavelength analysis provides us with an even more interesting workbench for the study of the ISM. For Instance, the combined UV and X-ray spectroscopy of background AGN allows to search for clouds that belong to the circumgalactic (CGM) or to the intergalactic (IGM) medium. The study of these clouds probes the evolution of the Galactic halo and its interaction with the surrounding CGM. In Chapter 4 we have presented a complete analysis of the interstellar and circumgalactic medium towards the bright AGN Mrk 509 through high-quality spectra taken with XMM-Newton, Hubble Space Telescope, and FUSE. We have detected and analyzed seven different cloud systems along this LOS. The single low- and three intermediate-velocity clouds (LVC and IVCs, \( v \lesssim 100 \text{ km/s} \)) are characterized by three distinct main phases with different ionization states. The high-velocity clouds (HVCs, \( v \gtrsim 100 \text{ km/s} \)), which usually probe the Galactic halo and the CGM, have a different structure and in the LOS towards Mrk 509 they show just two ionized phases. They are highly ionized most likely as the result of the large exposure to the X-ray background and the interaction with the circumgalactic medium. The similar abundances and ionization structure suggest a common origin for these HVCs. They may be at the outskirt of an extragalactic cloud captured by the Galaxy. The LVC and one of the IVCs belong to interstellar gas co-rotating with the Galactic disk, as confirmed by the detection of dust and molecules at rest wavelengths. The location of two other IVCs is not well constrained, they might belong either to disk co-rotating gas or to Galactic fountains. The most accepted scenario suggests that LVCs represent gas commonly found in the Galactic disk, IVCs mostly indicate Galactic fountains, while HVCs originate in the extragalactic environment and are captured by the Galactic gravitational field. Extending this work to more LOS would give a reply to many open questions concerning the origin of these clouds and their effects on the metallicity of the Galactic ISM.
6.3 Nova ejecta and CSM

Stars enrich with metals the ISM, but the ratios between the metallic yields provided by certain types of stars are not yet well determined. Models of stellar evolution and metallic yields are not always in agreement. The observations can provide accurate and alternative results through which is possible to discriminate between different evolutionary models. Novae are an interesting subclass of cataclysmic variables consisting of an exploding white dwarf (WD) that pulls out its metal-rich matter in the surrounding medium. In Chapter 3 we have reported our analysis of the XMM-Newton spectrum of nova V2491 Cyg and showed that its ejecta are well described by highly (photo-)ionized and metal-rich expanding shells. Their abundances indicate that they were ejected from an O-Ne white dwarf. Cold circumstellar and interstellar matter including dust is also present. High abundances of O and N shows that the surrounding medium is significantly enriched with metals by the nova ejecta. Variations on time scales of hours occur both in the luminosity of the central source and in the ionization level and columns of the absorption shells. The expanding gas is responding almost instantaneously to the variations in the source ionizing continuum. This work is a pioneer, new approach to the study of nova ejecta and might provide a powerful alternative method to probe their interaction with the surrounding medium and their role in the enrichment of metals. There are several nova spectra in the archive of the Chandra and XMM-Newton satellites onto which this analysis can be easily extended. This will provide important information on the structure and chemistry of nova ejecta and their effects on the metallicity of the surrounding medium.

6.4 Prospects

It is worth to say that we are in the golden age of the ISM X-ray spectroscopy. The current and future X-ray satellites allow for accurate measurements of interstellar column densities, ionization states, depletion factors, abundances, and dynamics, which are useful to determine the chemical and physical states of all the phases of the ISM. This thesis is the first systematic, thorough study carried over this field and provided some powerful methods useful to investigate the ISM. We also succeeded in solving some of the issues concerning the ISM composition and chemistry raised in Chapter 1. However, it will be necessary to extend this work on a large scale involving more targets pointing to different Galactic regions and more instruments. More targets will provide a mapping of the diffuse ISM and more accurate estimates of abundance gradients in the Galaxy. More instruments, possibly also covering different energy domains such as far-UV and X-ray, will provide independent measurements for same ionic species. Moreover, some energy regimes contain transitions from species which are missing at other energies (see e.g. Chapter 4).

The exact molecular composition of the cold IS phase is still an issue. Si, Mg, Fe, and O are among the elements that most contribute to the total mass of molecular gas and dust, but are often found in the same molecular compound. Therefore, the simultaneous fits of their absorption edges respectively located at 6.7, 9.5, 17.5, and
23.0 Å are required. No current instrument is provided with high effective area and spectral resolution at these wavelengths, simultaneously. Therefore, the contemporary use of the spectrometers on board different satellites will provide the best workbench for this analysis. For instance, *Chandra*/HETGS is the best detector at wavelengths up to the Fe L-edge ($\lambda \lesssim 17.5$ Å), while *XMM-Newton*/RGS is the most sensible near the O K-edge ($\lambda \sim 23.0$ Å). Our working team at SRON is currently working on this multi-wavelength analysis and accurately measuring depletion factors and dust composition for both iron and oxygen (see e.g. Costantini et al. 2012).

The current X-ray satellites will be operating for most of this decade and a new X-ray mission (*Astro-H*, Takahashi et al. 2010) will be launched in two years from now. The soft X-ray Calorimeter Spectrometer (SXS) on board this satellite will combine for the first time high sensitivity and spectral resolution in the broad 0.3 – 12 keV energy

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**Figure 6.1:** Simulated spectrum of GS 1826–238 for a 100 ks observation with Astro-H/SXS. The spectral model refers to the (gas + dust) Model C as given in Chapter 2.
band (or $1 - 40 \, \text{Å}$), which allows a simultaneous analysis of the O, Ne, Mg, Si, and Fe absorption edges. In Fig. 6.1 I show a simulated Astro-H/SXS spectrum of the soft X-ray spectrum of the LMXB GS 1826–238. The absorption and emission models used here refer to Model C which is shown in Chapter 2. The Ne K and Fe L-edges are similar as those shown by XMM-Newton/RGS, while the Si and Mg K-edges are more evident and show stronger absorption features (for comparison see Fig. 2.8). In Fig. 6.2 there is a simulation of the Si K-edge of GX 5–1, a highly-absorbed LMXB (courtesy of E. Costantini). $F_{2-10\,\text{keV}} \sim 3 \times 10^{-8} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ and $N_{\text{H}} \sim 2.3 \times 10^{22} \, \text{cm}^{-2}$ have been measured from archival HETGS data. The data refer to the base line model (red solid line) which is pure gas absorption (with no depletion). This is compared with more realistic scenarios of depleted gas phase (90% Si depletion) + dust compounds. The models are such that the total column density of Si is kept constant. The shift and distortion of the edge with respect to pure gas absorption is noticeable. Effective area uncertainties should not exceed 4% at the Silicon edge. This shows that the simultaneous fits of Chandra, XMM-Newton, and Astro-H spectra will constrain the chemistry of the most abundant heavy elements: O, Ne, Mg, Si, and Fe. The comparison between their abundance gradients and the models for stellar yields will provide the ratios between the contributes to the ISM metallicity as given by evolved AGB stars and different types of supernovae. This will unravel the course of the chemical evolution in our Galaxy.

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**Figure 6.2:** Simulated 100 ks spectrum of LMXB GX 5–1 with Astro-H/SXS (courtesy of E. Costantini).
Nederlandse Samenvatting

Ons galactisch stelsel, ook wel bekend als “de Melkweg”, ziet eruit als een grote stad met honderden miljarden sterren. De sterren zijn ingebed in een zeer ijl gas dat “interstellair medium” (ISM) wordt genoemd. Het ISM bevat materie in de vorm van gas, stof en moleculen vergelijkbaar met sigarettenrook. Tijdens de oerknal werden alleen lichte elementen gevormd, zoals waterstof en helium, terwijl de meeste zwaardere elementen, zoals koolstof en uranium, later zijn gevormd door thermonucleaire explosies in het binnenste van sterren. Dit proces, ook wel bekend als “sterevolutie”, verrijkt het ISM met metalen en moleculen. Uit een deel van de interstellaire (IS) materie ontstaan nieuwe sterren, waarvan de chemische samenstelling verschilt van de vorige generatie sterren. Het ISM is dan ook de ideale partner van de sterren in de galactische evolutie en de hoeveelheid zware elementen in het ISM is een maat voor eerdere stellaire evolutie.

Röntgenspectroscopie is een krachtig instrument geworden om de chemische en fysische eigenschappen van het ISM te onderzoeken. In dit proefschrift presenteer ik een succesvolle methode om de hoeveelheid metalen en stof in het ISM te meten door middel van observatie van hun absorptielijnen in de röntgenspectra van achtergrondbronnen. Bijvoorbeeld, de hoeveelheid (of abundantie) van metalen neemt toe in de richting van het galactisch centrum, en dat duidt op een snellere ontwikkeling in de binnenste regionen.

7.1 De Melkweg en zijn ziel: het ISM

Het grootste deel van het zichtbare licht in de Melkweg wordt uitgezonden door sterren en wordt deels geabsorbeerd door een donker, koud interstellair (IS) stof dat in de buurt van het melkwegvlak ligt. Deze materie is bijna onzichtbaar voor het blote
oog (optische energie-band), maar straalt sterk in het infrarood en radio-banden (zie Fig. 7.1). IS gas en stof worden meestal aangetroffen in een dunne schijf met een dikte ongeveer een tiende van de straal bedraagt, en gecentreerd is met het galactisch centrum. Het ISM bevat minder dan 10% van de galactische massa, maar levert het materiaal waaruit nieuwe generaties sterren ontstaan. Zonder deze continue toever van materie zouden er geen nieuwe sterren kunnen worden gevormd, zou de galactische levenscyclus ophouden te bestaan en zou het melkwegstelsel geleidelijk afkoelen en donkerder worden. Daarom kan het ISM worden beschouwd als de “levende ziel” van de Melkweg.

Temperaturen en dichtheden van de IS materie lopen sterk uiteen ten gevolge van de dynamische processen van stervoluitie en de effecten van verschillende warmtebronnen, zoals kosmische straling. Het interstellaire medium komt grofweg voor in drie fases, afhankelijk van de temperatuur van het gas. 1) De koude fase bevat stof, moleculen en gas bij temperaturen onder -170 °C. Deze koude materie is zwak geïoniseerd door sterlicht en kosmische straling, en wordt vervolgens verwarmd door fotoelektronen afkomstig van aangegraald stof. 2) De warme fase bestaat uit gas met een temperatuur van ongeveer 10 000 °C. Het is gedeeltelijk geïoniseerd door UV-straling.
van hete jonge sterren. 3) De hete fase is sterk geioniseerd en verhit tot ongeveer 1 miljoen °C door schokgolven, die afkomstig zijn van supernova-explosies. Het wordt ook wel “coronaal gas” genoemd, omdat de fysische toestand zeer vergelijkbaar is met die van stercorona’s.

Hoewel het meeste ISM-licht wordt uitgezonden bij golflengten buiten de zichtbare band, is er een aantal interstellaire wolken die mooie figuren aan de hemel creëren. De zogenaamde paardenkopnevel is een wolkencomplex dat kenmerken van verschillende interstellaire fasen laat zien (zie Fig. 7.2). De koude en donkere stofwolken (met de vorm van een paardenkop) verduisteren het licht afkomstig van de achterliggende emissienevel. De emissienevel bestaat uit warm geioniseerd gas dat wordt verhit door de nabijgelegen jonge sterren. De heldere blauwe nevels zijn wolken van interstellair stof die het licht van nabijgelegen sterren reflecteren. De energie van deze sterren is onvoldoende om het gas van de nevel te ioniseren zodat een emissienevel ontstaat, maar het is genoeg om stof zichtbaar te maken.

7.2 Verrijking van het ISM met metalen

Na de oerknal bestond de materie in het heelal alleen maar uit lichte elementen, zoals waterstof (H), helium (He), lithium (Li) en beryllium (Be). Zwaardere elementen, zoals koolstof en uranium (in de astronomie worden alle elementen zwaarder dan helium ook wel metalen genoemd), zijn later gevormd in de loop van de stellaire evolutie door nucleosynthese in de kernen van sterren. De chemische samenstelling van het ISM is vergelijkbaar met die van de zon: ongeveer 75% van de massa bestaat uit H, en 24% uit He. Hoewel de metalen slechts 1% van de totale massa uitmaken zijn ze van cruciaal belang om de chemische samenstelling en fysische toestand van het gas te verklaren.

Aggregaten bestaande uit stikstofatomen, moleculen en stof worden voornamelijk gevormd in geëvolueerde middelzware (AGB) sterren. Elementen zwaarder dan Si (silicium), zoals Ca (calcium), Fe (ijzer) en Ni (nikkel) worden meestal door type Ia supernova’s (SN Ia) geproduceerd. Dit is een spectaculaire explosie van een witte dwergster die geleidelijk massa opneemt van een begeleider tot het moment dat de ontstekingsstemperatuur voor koolstoffsusie wordt bereikt. Binnen een paar seconden ondergaat een aanzienlijk deel van de materie in de witte dwerg een kettingreactie, waarbij genoeg energie vrijkomt om de ster te laten exploderen als een supernova. Een type II supernova (SN II, ook wel supernova met kern-implosie genoemd) ontstaat uit de snelle ineenstorting en krachtige explosie van een zware ster. SN II produceren het merendeel van de interstellaire zuurstof (O) en neon (Ne). Het gehalte aan zware elementen is zodoende een directe afspiegeling van geschiedenis van de stervoluit.
Figure 7.2: De paardenkopnevel is een magnifieke interstellaire stofwolk die is gevormd uit stellaire winden en straling en een herkenbare vorm heeft aangenomen. Het is ingebed in de uitgestrekte en complexe Orionnevel. De donkere moleculaire wolk, ongeveer 1500 lichtjaren van de aarde, is alleen zichtbaar omdat het verduisterende stof zich aftekent tegen de heldere rode emissienevel IC 434. De heldere blauwe reflectienevel NGC 2023 is zichtbaar links onderaan. De opname is gemaakt met de grote 3.6-m Canada-France-Hawaii Telescope in Hawaii, USA.

langrijk omdat ze het grootste bestanddeel van de stofmassa vormen. Verschillende studies hebben bevestigd dat in de gasachtige fase ongeveer 60% van de koolstof en meer dan 90% van het magnesium, silicium en ijzer ontbreken (of verminderd aanwezig zijn), en vermoedelijk opgesloten zitten in stofdeeltjes. Zuurstof toont ook een significante vermindering tot 40%, maar het is niet duidelijk welke verbindingen dat kunnen verklaren. Als we alle mogelijke bijdragen van silicaten, koolstofhoudende oxides en ijs bij elkaar optellen, dan ontbreekt nog steeds ongeveer 25% van alle zuurstof.
Het ISM produceert verschillende emissie- en absorptieverschijnselen in röntgenstral- ing. Toch is röntgen-astrofysica van het ISM een zeer jonge wetenschap. De ontwikke- ling daarvan begon in de jaren ’70 met de ontdekking van de hete fase in het ISM door middel van raketmissies. Belangrijke verbeteringen in de studie van de emissie van het hete gas waren mogelijk door de lancering van de ROSAT satelliet, waardoor verschillende galactische röntgenbronnen zijn ontdekt. Een nieuw tijdperk van rönt- genspectroscopie brak aan na de lancering van de Chandra en XMM-Newton missies. De spectrometers aan boord van deze satellieten bezitten een grote gevoeligheid en hoge spectrale resolutie, waardoor het mogelijk is om heel nauwkeurig absorptie- en emissie-kenmerken te meten die door het ISM geproduceerd worden. In Fig. 7.3 toon ik een mozaïek van 400 bij 900 lichtjaar van verschillende Chandra-beelden van de binnenste delen van de Melkweg, dat honderden röntgenbronnen laat zien, zoals witte dwergen, neutronensterren en zwarte gaten, ingebed in een gloeiende mist van gas met een temperatuur van miljoenen graden. Dit hete gas lijkt te ontsnappen uit het galactisch centrum. Het werd verrijkt met zware elementen uit de regelmatig optredende stellaire explosies en zal uiteindelijk worden verspreid naar de galactische buitenwijken, waardoor de Melkweg zich weer verder ontwikkelt. Het centrum van onze Melkweg is eveneens van belang omdat het een uitstekend laboratorium is om de kernen van andere melkwegstelsels te bestuderen en te begrijpen.

Röntgenemissie is alleen geschikt voor het onderzoeken van de hete ISM fase. In röntgenspectra van achtergrondsbronnen laat het ISM absorptie-sporen na in een breed scala van energieën en in de meest uiteenlopende vormen en fasen (stof, moleculen, neutraal en geioniseerd gas). Elk element produceert bepaalde specrale kenmerken die lijken op een streepjescode. Wanneer astronomen sterren observeren, dan vergelijken ze hun spectra met laboratoriumgegevens, d.w.z. de streepjescode van verschil-
lende elementen, zoals zuurstof, neon, magnesium en ijzer. Sterke pieken (emissielijnen) of diepe dalen (absorptielijnen) in de waargenomen spectra zijn karakteristiek voor bepaalde elementen, en het is zo ook mogelijk om de hoeveelheid van elk element af te leiden (zie bijvoorbeeld Fig. 7.4). Absorptie-kenmerken van de ISM werden begin deze eeuw bij toeval ontdekt en wezen op de aanwezigheid van neutrale zuurstof, neon en ijzer. Speciale studies leidden tot de ontdekking van neutrale, enkelvoudige en dubbel geioniseerde atomen (vooral zuurstof en neon). De eerste metingen van de abundanteieverhouding Fe/H in de ISM en hun vergelijking met de abundantieverhouding Fe/H van de zon lieten zien dat ijzer duidelijk ontbreekt (of verminderd aanwezig is) in de IS gasfase, en mogelijk is vastgelegd in stofdeeltjes. Complexere structuren nabij de K-absorptiekant van zuurstof laten zien dat zuurstof misschien voor een deel zit opgesloten in IS stof of moleculen zoals hematiet, silicaten en ijs.

7.4 Dit proefschrift: doelen en resultaten

Het is duidelijk dat röntgenspectroscopie een belangrijk hulpmiddel is voor verder onderzoek van het ISM. De huidige röntgensatellieten leveren nauwkeurige schattingen van de hoeveelheid en ontbrekende fractie van metalen in de ISM en hun temperaturen. Diverse open vragen moeten nog beantwoord worden. Wat is de moleculaire samenstelling van de koude interstellaire fase? Welke fractie van ieder element zit opgeslagen in stof? Verkeren bepaalde fasen in een zekere evenwichtstoestand en zo ja, welke? Wat zijn de totale abundenties van de elementen? Hoe verhouden al deze parameters zich tot het specifieke galactische milieu? Hoe correleren abundantiepatronen in de Melkweg met de metaal-verrijking die door AGB sterren en supernovae worden geproduceerd? Dit proefschrift beantwoordt een aantal van deze vragen door middel van de analyse van de IS absorptielijnen in röntgenspectra van heldere achtergrondsbronnen.

Het diffuse ISM: structuur, samenstelling en homogeniteit

Ik heb IS absorptielijnen in de röntgenspectra van actieve galactische kernen (AGN) en röntgendubbelsterren bestudeerd, en ik heb gemeten welke fractie van de elementen C, N, O, Ne, Mg, Si en Fe aanwezig is in de vorm van moleculen, atomen en geioniseerd gas. Het diffuse ISM is meestal samengesteld uit een complex mengsel van gas in diverse fasen, stof en moleculen. De totale abundenties (gas + stof) van de koude IS fase nemen toe in de richting van het galactisch centrum, waaruit blijkt dat de stellaire evolutie in binnenste regionen van het melkwegstelsel sneller verloopt. In het algemeen verschilt de toenamesnelheid per element en dat suggereert dat de metaal-verrijking van het ISM door AGB sterren, SN I en SN II binnen het melkwegstelsel varieert. Stof is alomtegenwoordig en bevat ongeveer 15–20% van alle zuurstof en 70–90% van het ijzer. De hoeveelheid en samenstelling van stof lijkt constant te zijn in de galactische schijf. Ongeveer 10% van het gas is geioniseerd, en de verhouding tussen de verschillende ionisatietoestanden (die de temperatuur van elke fase bepalen) is ongeveer constant over de schijf. Dit suggereert dat het ISM op grote schaal chemisch homogen is. Tot slot, de overeenstemming tussen de IS zuurstof abundante en de gemeten waar-
7.4 Dit proefschrift: doelen en resultaten

Figure 7.4: XMM-Newton spectrum van nova V2491 Cyg. De uitgestoten materie werd gemodelleerd door schillen van foto-geïoniseerd gas met een snelheid van 3000 km/s. Let op de sterke absorptielijnen van hoog-geïoniseerd O en N.

den voor nabijgelegen jonge sterren, H II gebieden en planetaire nevels, bevestigt dat de Melkweg lokaal ook chemisch homogeen is.

Het lokale CSM en nova ejecta

De metaalproductie van bepaalde soorten sterren is nog steeds niet goed bekend. Sterrevolutie-modellen zijn niet altijd met elkaar in overeenstemming en soms leveren de waarnemingen bruikbaardere resultaten. Nova’s zijn exploderende witte dwergsterren (WD), die een deel van haar metaalrijke materie in het omringende circumstellaire medium (CSM) blazen. Het XMM-Newton spectrum van nova V2491 Cyg liet zien dat de ejecta goed kunnen worden beschreven als schillen materia die met een snelheid van 3000 km/s uitzetten, en die foto-geïoniseerd en verhit worden door de exploderende WD (zie Fig. 7.4). Absorptie door koud gas met lage snelheden ($v < 100$ km/s) vindt plaats in circumstellaire en interstellaire materie die stof bevat. De abundanties van de schillen geven aan dat ze werden uitgeworpen door een O–Ne/N
witte dwerg. De hoge O en N gehalten in het koude absorberende gas laten zien dat het omringende medium aanzienlijk verrijkt is met metalen door de nova ejecta.

**Verschillende omgevingen: ISM, CGM en IGM**

Met spectraalanalyse in diverse golf lengtegebieden (ultraviolet (UV) en röntgen) van actieve galactische kernen (AGN) kan men ook wolken onderzoeken die deel uitmaken van het circumgalactisch (CGM) of het intergalactisch medium (IGM), en hun interactie met de halo van de Melkweg. Ik heb het ISM en het CGM in de richting van de heldere AGN Mrk 509 geanalyseerd door middel van traliespectra van hoge-kwaliteit genomen met XMM-Newton (röntgen), de Hubble Space Telescope en FUSE (UV-band). Langs de gezichtslijn liggen zeven complexe wolkensystemen. De hoge-snelheid wolken ($v \approx 100 \text{ km/s}$) zijn sterk geioniseerd, waarschijnlijk ten gevolge van botsing met de galactische halo en een grotere blootstelling aan de röntgen-achtergrondstraling. Hun abundanties en ionisatie-structuur zijn vergelijkbaar, hetgeen suggereert dat zij zich mogelijk bevinden op de rand van een enkele extragalactische wolk (zie Fig. 7.5). De wolken met een lage en middelmatige snelheid ($v < 100 \text{ km/s}$) bestaan waarschijnlijk uit interstellair gas dat mee-roteert met de galactische schijf.

### 7.5 Vooruitzichten

We bevinden ons in de *gouden eeuw* van de ISM röntgenspectroscopie. De huidige en toekomstige röntgensatellieten zorgen voor nauwkeurige metingen van de temperaturen, de hoeveelheid en samenstelling van het stof, de metaalabundanties en de snelheden die de chemische en fysische structuur van het ISM bepalen. Dit proefschrift is de eerste systematische, grondige studie uitgevoerd op dit gebied en presenteert een krachtige methode om het ISM te onderzoeken. Het is echter noodzakelijk om dit werk grootschaliger op te zetten met meerdere gezichtslijnen (d.w.z. meer bronnen) en verschillende instrumenten om het ISM nog beter in kaart te brengen, en nauwkeurige schattingen van abundantiepatronen in de Melkweg te verkrijgen. De huidige röntgensatellieten zullen voor het merendeel van dit decennium operationeel zijn, en de nieuwe röntgenmissie *Astro-H* zal binnen twee jaar worden gelanceerd. De *soft X-ray Calorimeter Spectrometer* aan boord van deze satelliet zal voor het eerst een hoge spectrale resolutie in een brede energieband van 0.3 tot 12 keV (of $1 - 40 \text{ Å}$), in combinatie met een hoge gevoeligheid, waardoor een gelijktijdige analyse van de Fe, Ne, Mg en Si spectra mogelijk wordt. Samen met *Chandra* en XMM-Newton zal *Astro-H* de chemie van zware elementen zoals O, Mg, Si en Fe ontrafelen. De vergelijking van hun abundantiepatronen met de modellen van stellaire evolutie zal onthullen hoe het ISM verrijkt met metalen van AGB sterren en verschillende soorten supernova’s. En hiermee wordt het verloop van de chemische evolutie van ons melkwegstelsel vastgelegd.
Figure 7.5: Artistieke weergave van drie hoge snelheid wolken (A, B en C) in botsing met de halo van ons melkwegstelsel. De wolken van lage en middelmatige snelheid (D t/m G) worden verondersteld deel uit te maken van de spiraalarmen.
Sommario italiano

La nostra Galassia, nota anche come “Via Lattea”, si presenta come una grande città dove vivono centinaia di miliardi di stelle. Le stelle sono circondate da nubi molto rade detto “mezzo interstellare” (ISM). L’ISM contiene materia sotto forma di gas e polvere simile al fumo di sigaretta. Il Big Bang ha creato solo gli elementi leggeri come l’idrogeno e l’elio nei primi istanti di vita dell’Universo, mentre la maggior parte degli elementi più pesanti dal carbonio all’uranio sono stati prodotti in seguito durante le reazioni termonucleari nei nuclei delle stelle. Questo processo, noto anche come evoluzione stellare, ha arricchito l’ISM di metalli e molecole. Parte della materia interstellare viene poi utilizzata per generare nuove stelle la cui composizione chimica differisce da quella delle precedenti generazioni. L’ISM è quindi il partner ideale delle stelle nell’evoluzione Galattica e la quantità di elementi pesanti nell’ISM sono la testimonianza dell’evoluzione stellare precedente. Tuttavia, nonostante i numerosi studi sull’ISM, la sua composizione chimica non è stata ancora determinata con accuratezza.

La spettroscopia a raggi X è diventata un potente strumento per studiare le proprietà chimiche e fisiche dell’ISM. In questa tesi mostro infatti un metodo efficace per misurare le quantità di metalli e polvere nell’ISM attraverso l’osservazione delle loro righe di assorbimento negli spettri a raggi X di sorgenti di fondo. Per esempio, la quantità (o abbondanza) di metalli risulta aumentare verso il centro della Galassia indicando un’evoluzione più veloce nelle sue regioni interne.

8.1 La Galassia e la sua anima: l’ISM

La maggior parte della luce visibile nella Via Lattea è emessa dalle stelle e viene in parte assorbita da una polvere interstellare oscura e fredda che si trova in prossimità del piano galattico. Questa materia è quasi invisibile all’occhio nudo (banda di energia ottica), ma emette fortemente nelle bande infrarosse e radio (vedi in Fig. 8.1). Gas
e polveri interstellari si trovano principalmente all’interno di un disco sottile, il cui centro coincide con quello della Galassia. Questo disco gassoso viene detto sottile in quanto il suo spessore è circa 10 volte più piccolo del suo raggio. L’ISM contiene meno del 10% della massa galattica, ma fornisce la fonte di materia per le nuove generazioni di stelle. Senza questo continuo apporto di materia nessuna nuova stella verrebbe creata, il ciclo di vita galattica si fermerebbe, e la Galassia si spegnerebbe progressivamente. Pertanto, l’ISM può essere considerato come l’anima vivente della Galassia.

La materia interstellare possiede temperature e densità molto varie, che sono dovute ai diversi processi dinamici di evoluzione stellare e agli effetti di diverse fonti di calore, come ad esempio i raggi cosmici. Tuttavia, la maggior parte della materia si struttura in tre fasi caratteristiche, ognuna delle quali con un certo regime di temperatura.
1) La fase fredda contiene polvere e gas a temperature inferiori a circa -170°C. Questa materia fredda è debolmente ionizzata dalla luce delle stelle e dei raggi cosmici e viene poi riscaldata da fotoelettroni irradiati dalla polvere.
2) La fase tiepida è costituita da gas con temperature di circa 10 000°C. Essa è in parte fotoionizzata dall’emissione UV di stelle giovani e calde.
3) La fase calda possiede gas altamente ionizzato e riscaldato fino a circa 1 milione di
8.1 La Galassia e la sua anima: l’ISM

Figure 8.2: La Nebulosa Testa di Cavallo è una magnifica nube di polvere interstellare che è stata scolpita da venti e radiazioni stellari fino ad assumere una forma riconoscibile. È incorporata nella vasta e complessa Nebulosa di Orione. L’oscura nube molecolare, distante circa 1500 anni luce, è visibile solo perché la sua polvere oscura si pone dinanzi alla nebulosa luminosa, rossa ad emissione IC 434. La nebulosa blu a riflessione NGC 2023 è visibile in basso a sinistra. L’immagine è stata ottenuta dal grande 3,6 m Canada-France-Hawaii Telescope alle Hawaii, Stati Uniti d’America.

gradi dalle onde d’urto provenienti da esplosioni di supernova. Esso è anche chiamato gas coronale perché il suo stato fisico è molto simile a quello delle corone stellari.

Sebbene L’ISM emette maggior parte della luce a lunghezze d’onda al di fuori della banda visibile, ci sono alcune nubi interstellari che producono stupende immagini nel cielo. La cosiddetta Nebulosa Testa di Cavallo è un complesso di nubi che mostrano i segni di diverse fasi interstellari (vedi la Fig. 8.2). La fredda e oscura polvere interstellare (con la forma a testa di cavallo) oscura la luce proveniente dalla nebulosa ad emissione retrostante. La nebulosa ad emissione è costituita da gas caldo ionizzato e riscaldato dalla luce proveniente da stelle giovani e calde nei suoi pressi. Le luminose nebulose blu sono nubi di polvere interstellare che riflettono la luce delle stelle vicine. L’energia di queste stelle è insufficiente ad ionizzare il gas della nebulosa per creare una nebulosa a emissione, ma è sufficiente a rendere visibile la polvere per diffusione.
8.2 Arricchimento di metalli dell’ISM

Il Big Bang diede origine soltanto agli elementi leggeri come idrogeno (H), elio (He), litio (Li) e berillio (Be). Elementi più pesanti come quelli dal carbonio all’uranio (in astronomia tutti gli elementi più pesanti dell’elio sono spesso chiamati metalli) sono stati formati dopo nel corso dell’evoluzione stellare attraverso la nucleosintesi nei nuclei stellari. La composizione chimica dell’ISM è simile a quella del Sole: circa il 75% e il 24% in massa vengono forniti da H ed He, rispettivamente. Sebbene i metalli contengano solo il restante 1% della massa totale, essi sono cruciali per comprendere la composizione chimica e lo stato fisico del gas.

Azoto atomico, molecole e polveri si formano principalmente in stelle evolute di media massa (stelle AGB). Gli elementi più pesanti del silicio, come ad esempio calcio, ferro e nichel, sono principalmente forniti dalla supernova di tipo Ia (SN Ia). Si tratta di una violenta esplosione di una nana bianca che accresce a poco a poco materia da una stella compagna fino al punto in cui si raggiunge la temperatura sufficiente ad innescare la fusione di carbonio. Nel giro di pochi secondi una frazione sostanziale della materia della nana bianca subisce una reazione a catena, rilasciando energia sufficiente ad esplodere la stella in una supernova. Un supernova di tipo II (SN II, nota anche come supernova a collasso nucleare) rappresenta il rapido collasso e l’esplosione violenta di una stella massiccia. Supernove di questo tipo forniscono la maggior parte dell’ossigeno e del neon interstellari. Pertanto, è chiaro che gli elementi pesanti testimoniano direttamente la storia della passata evoluzione stellare. Nei primi anni di vita dell’Universo, l’arricchimento di metalli è stato guidato dalle SN Ia, perché il tipo Ia richiede molto più tempo per esplodere. Questo indica che il gas interstellare è stato dapprima arricchito di elementi come ossigeno e silicio. Successivamente, quando le SN Ia hanno iniziato a esplodere, gli elementi più pesanti come il ferro e nichel sono divenuti più abbondanti.

Carbonio, ossigeno, magnesio, silicio e ferro sono anche importanti perché contengono la maggior parte della massa in polvere. Diversi studi hanno confermato che circa il 60% di carbonio e più del 90% di magnesio, silicio e ferro mancano (o sono esauriti) nella fase gassosa e sono presumibilmente rinchiusi in granuli di polvere. L’ossigeno mostra fattori di esaurimento fino al 40%, ma non si capisce bene quali composti molecolari possano giustificare tali valori. Se sommiamo tutti i possibili contributi forniti da silicati, ossidi di carbonio e ghiacci, c’è ancora un 25% di ossigeno mancante (se confrontati con l’abbondanza di ossigeno nel sistema solare).

8.3 Telescopi a raggi X: nuovi occhi puntati sull’Universo

Nei raggi X l’ISM produce svariati fenomeni di emissione ed assorbimento, tuttavia l’astrofisica nei raggi X dell’ISM è una scienza molto giovane, il cui sviluppo è iniziato con la scoperta della fase interstellare calda negli anni ’70 attraverso il lancio di razzi e satelliti muniti di rivelatori per raggi X. Miglioramenti importanti nello studio dell’emissione del gas caldo sono stati forniti dal lancio del satellite ROSAT, che ha portato alla scoperta di diverse sorgenti galattiche di raggi X. Dopo il lancio delle missioni
8.3 Telescopi a raggi X: nuovi occhi puntati sull’Universo

Figure 8.3: Questo mosaico di immagini Chandra della regione centrale della nostra Galassia rivela centinaia di nane bianche, stelle di neutroni e buchi neri circondati da gas caldo in emissione. Il buco nero al centro della Galassia si trova all’interno della chiazza bianca e luminosa nel centro dell’immagine. I colori indicano bande di energia di raggi X - rosso (bassa), verde (media) e blu (alta). Credit: NASA / UMass / D.Wang et al.

Chandra e XMM-Newton una nuova era per la spettroscopia a raggi X è stata inaugurata. Gli spettrometri a bordo di questi satelliti sono dotati di sensibilità e risoluzione spettrale elevate in grado di misurare con precisione profili di assorbimento ed emissione prodotti dall’ISM. In Fig. 8.3 mostrò un mosaico di 400 x 900 anni luce di diversi immagini Chandra delle regioni più interne della Via Lattea, che rivela centinaia di sorgenti di raggi X, come nane bianche, stelle di neutroni e buchi neri incorporati in una nebbia incandescente di gas di svariati milioni gradi. Questo gas caldo sembra essere in fuga dal centro galattico. Il gas è stato arricchito di elementi pesanti dalla frequente distruzione stellare e li distribuirà nei sobborghi del sistema galattico influenzandone l’evoluzione. Il centro della nostra Galassia è importante anche perché fornisce un eccellente laboratorio per conoscere i nuclei di altre galassie.

Tuttavia, lo studio dell’emissione di raggi X è adatto solo per sondare la fase calda dell’ISM. Negli spettri ad raggi X delle sorgenti di fondo le varie forme e fasi interstELLari (polvere, molecole, gas atomico e ionizzato) producono profili di assorbimento per una vasta gamma di energie. Ogni elemento produce una certa quantità di tracce spettrali simili ad un codice a barre. Quando gli astronomi osservano le stelle, confrontano i loro spettri con quelli presi in laboratorio per diversi tipi di elementi come ossigeno, neon, magnesio e ferro (i suddetti “codici a barre”). Intensi picchi (noti come righe di emissione) o avvallamenti (righe di assorbimento) negli spettri osservati sono quindi identificati come le tracce lasciate da certi elementi. Dalle loro intensità è anche possibile ricavare la quantità di ciascun elemento (si veda ad esempio la Fig. 8.4). Nei primi “anni 2000”, profili e righe di assorbimento vennero scoperti per caso e rivelarono la presenza di ossigeno, neon e ferro neutri nell’ISM. Studi accurati hanno portato alla scoperta di molte specie neutre e ionizzate (per lo più di ossigeno e neon). Le prime misure dei rapporti di abbondanza tra ferro e idrogeno nell’ISM e successivo confronto con i rispettivi valori solari ha dimostrato che il ferro è significativamente mancante (o esaurito) nella fase interstellare gassosa e, eventualmente, rinchiuso in granuli di polvere. Strutture complesse scoperte vicino al profilo di assorbimento
della shell K dell’ossigeno hanno mostrato che una parte significativa dell’ossigeno interstellare potrebbe essere immagazzinata in polvere o molecole come ematite, silicati e ghiacci.

8.4 Questa tesi: obiettivi e risultati


ISM diffuso: struttura, composizione e omogeneità

Ho studiato righe di assorbimento interstellare negli spettri di raggi X di nuclei galattici attivi (AGN) e binarie di fondo ed ho misurato le quantità di gas molecolare, atomico e ionizzato per svariate forme di C, N, O, Ne, Mg, Si e Fe. L’ISM diffuso è generalmente composto da una miscela complessa di gas multi-fase e polveri. Tutte le abbondanze totali (gas + polvere) della fase fredda aumentano verso il centro galattico e indicano che l’evoluzione stellare procede più velocemente nelle regioni interne della Galassia. I gradienti delle abbondanze dei vari elementi sono generalmente diversi e suggeriscono che i contributi arricchimento di metalli nell’ISM forniti da stelle AGB, SN Ia e SN II variano all’interno della Galassia. La polvere è sempre presente nel disco galattico e contiene circa il 15–20% e il 70–90% di ossigeno e ferro, rispettivamente. La quantità e la composizione della polvere interstellare sembrano non variare all’interno di tale disco. Circa il 10% del gas è ionizzato, ma i rapporti tra le quantità di gas trovato ai diversi stati di ionizzazione sono simili attraverso il disco, essi forniscono la temperatura di ciascuna fase. Questo suggerisce che su larga scala l’ISM diffuso è chimericamente omogeneo. Infine, l’accordo tra la abbondanza di ossigeno interstellare e il valore misurato per giovani stelle, regioni H II e le nebulose planetarie vicine conferma che localmente anche la Galassia è chimicamente omogenea.

CSM locale e materia espulsa intorno ad una nova

Il rendimento in metalli fornito da alcuni tipi di stelle non è stato ancora ben determinato. I modelli di evoluzione stellare non sono sempre consistenti e qualche volta le osservazioni possono fornire risultati più precisi ed alternativi. Le cosiddette stelle nova consistono di una nana bianca che esplode ed espelle parte della sua materia ricca di metalli nel mezzo circumstellare circostante (CSM). Lo spetto
XMM-Newton della nova V2491 Cyg ha dimostrato che il suo materiale espulso è caratterizzato da strati gassosi in espansione ad una velocità di circa 3000 km/s, i quali sono fotoionizzati e riscaldati dall’esplosione sulla nana bianca (vedi Fig. 8.4). La luce emessa dall’esplosione è parzialmente assorbita da un mezzo freddo con bassa velocità ($v < 100$ km/s) contenente polvere. Parte di esso risiede nello spazio interstellare lungo la linea di vista e il resto si trova nel CSM intorno alla stella. Le abbondanze degli strati indicano che sono stati espulsi da una nana bianca a prevalenza di ossigeno e neon e povera di carbonio. Abbondanze elevate di ossigeno e azoto del gas freddo indica che il mezzo circostante è stato notevolmente arricchito di metalli dal materiale espulso dalla nova.

**Ambienti diversi: ISM, CGM, and IGM**

L’analisi a diverse lunghezze d’onda (come ad esempio i raggi UV ed X) di AGN di fondo permette di indagare su nubi che appartengono anche al mezzo circumgalattico.
(CGM) o intergalattico (IGM) e sulla loro interazione con l’alone galattico. Ho analizzato l’ISM e il CGM verso il luminoso AGN Mrk 509 con spettri di elevata qualità ottenuti con XMM-Newton (nei raggi X), Hubble Space Telescope e FUSE (nella banda UV). Sette sistemi complessi di nubi si trovano lungo questa linea di vista. Le nubi ad alta velocità ($v \gtrsim 100$ km/s) sono altamente ionizzate molto probabilmente a causa dell’elevata esposizione al fondo di raggi X e dell’interazione collisionale con l’alone galattico. Le loro abbondanze e gradi di ionizzazione simili suggeriscono che potrebbero trovarsi nella periferia di una nube extragalattica (vedi Fig. 8.5). Le nubi a bassa e media velocità ($v \lesssim 100$ km/s) sono più probabilmente gas interstellare che ruota con il disco galattico.

**Figure 8.5:** Vista artistica di tre nubi ad alta velocità (A-to-C) che impattano l’alone galattico. In questo scenario le nubi a bassa e media velocità (D-to-G) appartengono a bracci di spirale della Galassia.
8.5 Prospettive per il futuro

Ci troviamo nell’*età d’oro* della spettroscopia a raggi X del mezzo interstellare. I satelliti a raggi X attuali e futuri consentono di misurare con precisione temperature, quantità e composizione in polvere, abbondanze metalliche e dinamiche delle nubi interstellari ovvero quei parametri che determinano la struttura chimica e fisica dell’ISM. Questa tesi è il primo studio sistematico ed approfondito svolto in questo settore e fornisce un metodo efficace per studiare l’ISM. Tuttavia, è necessario estendere questo lavoro su una larga scala che coinvolga più linee di vista (ovvero più sorgenti) e diversi strumenti per una mappatura migliore dell’ISM e per stime accurate dei gradienti di abbondanza all’interno della Galassia. Gli attuali satelliti a raggi X saranno operativi per la maggior parte di questo decennio e la nuova missione nei raggi X *Astro-H* sarà lanciata in due anni a partire da adesso. Lo spettrometro a calorimetro nei raggi X a bordo di questo satellite fornirà per la prima volta un’alta risoluzione spettrale nella banda di energia 0,3 – 12 keV (ovvero 1 – 40 Å) combinata con un’elevata sensibilità e la possibilità di una analisi simultanea di Fe, Ne, Mg e Si. Insieme a *Chandra* ed *XMM-Newton, Astro-H* sbroglierà la chimica di elementi pesanti come O, Mg, Si e Fe. Il confronto tra i loro gradienti di abbondanza ed i modelli di evoluzione stellare rivelaranno come l’ISM è stato arricchito di metalli dalle stelle AGB e dai diversi tipi di supernove. Questo lavoro descriverà il corso dell’evoluzione chimica della nostra Galassia.
Appendix A

Appendix to Chapter 2: Absorption by oxygen molecules

The amol model calculates the transmission of various molecules. Presently only the oxygen edge is taken account of. Updates of this model, once made, will be reported in the manual of SPEX. The following compounds are presently taken into account (see Table A.1).

The chemical composition of these minerals was mainly taken from the Mineralogy Database of David Barthelmy. We take the cross-sections from the references as listed in Table A.1 in the energy interval where these are given, and use the cross section for free atoms Verner & Yakovlev (1995) outside this range. van Aken et al. (1998) do not list the precise composition of iron oxide. We assume here that \( x = 0.5 \).

Some remarks about the data from Barrus et al. (1979): not all lines are given in their tables because they suffered from instrumental effects (finite thickness absorber combined with finite spectral resolution). However, Barrus et al. have estimated the peak intensities of the lines based on measurements with different column densities, and they also list the FWHM of these transitions. We have included these lines in the table of cross sections and joined smoothly with the tabulated values.

For \( \text{N}_2\text{O} \), the fine structure lines are not well resolved by Barrus et al. Instead we take here the relative peaks from Wight & Brion (1974), that have a relative ratio of 1.00 : 0.23 : 0.38 : 0.15 for peaks 1, 2, 3, and 4, respectively. We adopted equal FWHMs of 1.2 eV for these lines, as measured typically for line 1 from the plot of Wight & Brion (1974). We scale the intensities to the peak listed by Barrus et al. (1979). Further, we subtract the C and N parts of the cross section as well as the oxygen 2s/2p part, using the cross sections of Verner & Yakovlev (1995). At low energy, a very small residual remains,

1 http://webmineral.com/
### Table A.1: Molecules present in the amol model.

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<th>nr</th>
<th>name</th>
<th>chemical formula</th>
<th>reference</th>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>carbon monoxide</td>
<td>CO</td>
<td>a</td>
</tr>
<tr>
<td>3</td>
<td>carbon dioxide</td>
<td>CO₂</td>
<td>a</td>
</tr>
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<td>N₂O</td>
<td>a, b</td>
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<td>H₂O</td>
<td>c</td>
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<td>e</td>
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<td>9</td>
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<td>hercynite</td>
<td>FeAl₂O₄</td>
<td>e</td>
</tr>
</tbody>
</table>

references:

- a Barrus et al. (1979), 0.5-0.75 eV resolution
- b Wight & Brion (1974), 0.5 eV resolution
- c Hiraya et al. (2001), 0.055 eV resolution
- d Parent et al. (2002), 0.1 eV resolution
- e van Aken et al. (1998), 0.8 eV resolution

which we corrected for by subtracting a constant fitted to the 510–520 eV range of the residuals. The remaining cross section at 600 eV is about 10% above the Verner cross section; it rapidly decreases; we approximate the high-E behavior by extrapolating linearly the average slope of the ratio between 580 and 600 eV to the point where it becomes 1.
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Curriculum Vitae

I was born on 9th of April 1982 in Naples, Italy. I developed first interests in Astronomy since the last year of my primary school when I asked my father to buy me a small telescope to search for stars invisible to the naked eye. Later during the first school lectures on the birth of the Solar system I completely devoted my self to stars and their mysteries. Since then I already knew what would be my future.

After the scientific lyceum, I attended the University of Naples and obtained the degree in physics. Here I followed interesting laboratorie s for the solar observation and specialized in astrophysics in May 2008. At the Observatory of Capodimonte, Naples, I familiarized with different kinds of telescopes and devices through which I developed my observational skills. In Naples, I did my master degree research with Giuseppe Longo and Maurizio Paolillo focusing on the X-ray variability of active galactic nuclei as probe of black hole masses and accretion of matter.

I started my PhD research at SRON in November 2008 working on X-ray spectroscopy of the interstellar medium of our Galaxy with Frank Verbunt and Jelle Kaastra. I have traveled around the world and attended several interesting conferences that improved the quality of my work. Through the working visit at Jan-Uwe Ness (ESAC, Madrid, Spain) and Jerry Kriss (STScI, Baltimore, USA) I could work in rather different research fields concerning nova ejecta and circumgalactic medium. I have also worked as tutor in the University of Utrecht in the courses of General Relativity (with Peter Hoyng and John Heise) and Galaxies (with Soeren Larsen). This thesis summarizes the results of my PhD research obtained between November 2008 and October 2012. I will spend the next two / three years as post doc at the Institute of Astronomy in the University of Cambridge, UK, in the research group of Andy Fabian.
Acknowledgements

I was younger than 10 when me and my parents tried to understand why those little points in the sky had different colors. We did not really know the reasons for such a difference. This was just the beginning. My mother, Maria, subscribed me to the monthly journal “Video Astronomy” and as soon as I read about stars which cannot be seen with the naked eye, I asked my father, Ettore, to buy me a small efficient telescope to search for “invisible stars” and special features on planets and moons. A little amateur was just born. My interests in the Solar system were improved during the lectures at the intermediate and high school. Finally, I realized that stars have different colors due to their temperatures and chemistry, but how were the elements produced in the stars? How were they shared with the other stars in the Galaxy - this beautiful city hosting billions of different astronomical objects? These matters were part of the several interests which brought me to undergo physics studies and to specialize in astrophysics. It took me a while to understand that the more I learned, the wider the amount of question was. My eagerness in understanding the sky continuously grew up in these early 30 years of my life. I really hope that this trend will stand!

The development of this thesis was possible first of all because I reached SRON. This happened because my supervisors in Naples, Giuseppe Longo, Maurizio Paolillo, and Betty De Filippis, provided me the hints for carrying out a very interesting and up-to-date master thesis. Before them Massimo Capaccioli and Ester Piedipalumbo enabled me to write a bachelor thesis on the gravitational lensing phenomenon which turned out to be very helpful during my teaching in the Utrecht University with great persons like Peter Hoyng, John Heise, and Soeren Larsen. This manuscript shows the work of these last four years in the Netherlands. The most beautiful period of my life without any doubt. I am very thankful to my advisors Frank Verbunt, Jelle Kaastra and Elisa Costantini who guided me to the production of a highly interesting work. They taught me how to study scientific matters, to criticize results and to find solutions to different kinds of problems. Thanks to them I am not anymore the little, afraid student that came here 4 years ago. I want also to thank Jan-Uwe Ness (ESAC, Spain) and Jerry Kriss (STScI, US) who helped me to carry out this work with new ideas and invitation.
to visit them abroad. The LKBF (Leids Kerkhoven-Bosscha Fonds) provides me with the funds necessary for deepening my research through several business trips.

These four years at SRON were really amazing thanks to the people that surrounded me, especially in the beginning, such as Jacobo and Silvana, Rob, Ton, Manuel, Jelle de Plaa, Peter Jonker, Daniel, Lucien, Remco and Nynke, Wim, Jan-Willem, Jean, Esther and Marlies, Eva and Gio, Oliwia, Enya, Norbert, Peter den Hartog, Marianne, Chris, Pourja, Theo, Hiroki, and Artur. Many thanks also to Matthijs for the several amazing and useful discussions! Special thanks and hugs will be always reserved to my first officemate zen power Yan (and his wife Froukje), the only person able to handle with my fancy and funny jokes 24/7. He has been the best colleague, a good friend, and the living fun for me at SRON. I cannot imagine how would have been here without him. After he left, I luckily shared the office with Marianne, thanks to whom I still had a great time therein. Many thanks to all those colleagues that shared with me nice moments during the SRON science days, the Sinterklaas nights, the social meetings at the Utrecht University, and the work conferences I have attended.

These four “Dutch” years have been the most beautiful of my life thank to the many friends I made. I cannot name all, but the most important for me were Ariadne, Victor, Chantal, Gerry, Andre, Claudia, Ken, Renata, Jesse, Louise, Simona, Nita, Rohan, Rosa, Andrew, Ratna, Raffa, Rafael, Susha, Kyoko, Maarten and Cecile, Miguel, Sam, Emmy, Ivan, Davide, Edouard, Petteri, Rianna, Paulius, Giuseppe, Sheba, Paulo, Geza, Oluchi, Father Herman, Loraine, Thais, Rajani, Pawel, Brigitte, Sylvia, Eline, as well as my overseas friend and colleague Pierluigi. It is worth to say that you all made me a better person. Last but not least, I want to thank Peter Hoyng and my friend Wendy for helping me translating the summary of this thesis into Nederlandse. Thank you Peter for let it appearing suitable also for the public audience and still many thanks for the nice lectures of General Relativity we gave together at the Utrecht University. Wendy, mijn zielsverwant, the good and female version of me, thank you very much for the Dutch summary and for being the special between my friends. The beautiful time spent with you in the last Dutch summer showed me that I can feel like home even in a foreigner country. Thank you very much also for the many motivations provided me to complete my thesis and to continue my profession in UK. I will always keep you in my heart wherever we’ll be. Special thanks to Jelle de Plaa, the genius, for always helping me to solve software issues and to prepare such a beautiful thesis cover!

Una parte dei ringraziamenti, in Italiano, va dedicata alla mia stupenda famiglia. Come già detto, senza il supporto morale - e non solo - dei miei genitori, io non sarei arrivato certamente qui. Mi avete dato la forza ed il coraggio necessari per andare avanti nei miei studi e avete fatto di me un vero e proprio uomo. Sono svariate le persone della mia famiglia che amo e che mi hanno sempre supportato azzerando le distanze in questi quattro anni. Su tutti figurano i miei nonni, zii e cugini paterni, i miei suoceri e le mie sorelle Mara, Monica e Adele. Tuttavia, se per tutte queste persone riesco a trovare una maniera per essere riconoscente, credo che non troverò mai parole sufficienti a ringraziare mia moglie, Valentina, la mia compagna di vita da 10 anni a questa parte: un punto fermo nella mia esistenza, la pazienza e la forza grazie alle quali sono riuscito a superare ogni sorta di difficoltà. In tutti questi anni hai dato un senso alla mia vita e sei stata una compagna fedele e giudiziosa. Grazie amore mio.