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2. X-Ray Absorption Spectroscopy of NSSXT and Its Role in The Evaluation of ISM Composition Using XMM-Newton Data

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Abstract:

The development of High-Resolution Spectroscopy paved the path of evaluating X-ray absorption features. The absorption features in the spectra of X-ray binaries (particularly neutron star Soft X-ray Transients, NSSXT) could reveal the presence in the atmospheres of the neutron star or their magnetic field strength. Its efficacy in tracing the presence of the metal abundances in the Interstellar medium (ISM) in various forms is appreciably good. However, the possibility of multiple origins of absorption lines always makes it difficult to diagnose and ascertain the results and needs an elaborate and fine analysis to conclude. In this paper, an attempt has been made to summarise issues related to X-ray absorption spectroscopy and its scope in constraining the Interstellar Medium (ISM).

Keywords:

NSSXT, ISM, Spectroscopy, Absorption lines.

2.1 Introduction:

X-ray astronomy opened up a new dimension of understanding the universe, its dynamics, and various governing phenomena. The journey starts with the discovery of the first non-solar cosmic X-ray source Scorpius X-1 (Sco X-1) by Giaconni et al., 1962. Presently we have a sea of data because of the launching of a series of dedicated astronomical study satellites followed by the launching of the first X-ray satellite UHURU in 1970.

It was always challenging to study the matter surrounding the neutron star present in X-ray binaries. High-Resolution X-ray Spectroscopy (HRXS) evolved as a powerful tool to ease the task. It is in particular the absorption features in the spectra of X-ray binaries that could reveal the presence of atmospheres of the neutron star and their magnetic field strength. The study of X-ray absorption spectra helps us to detect the presence and abundance of elements from carbon to iron. X-ray Spectroscopy is also useful in probing larger column density because it is less affected by extinction and is thus very helpful for finding out the properties of the ISM across the galactic disk. The HRXS has turned up as a sustainable diagnostic tool for evaluating the chemical and physical properties of the ISM. Different charge states of the elements and transition from K-shell and L-shell allow us to constrain multiphase ISM, its ionization state, and temperature distribution.

The X-ray sky is dynamic and keeps on changing due to the sudden appearance of a bright new source in the sky. The brightness lasts maximum for a week and then it declines to its pre-burst level (Verbrunt, F. et al., 1996). The Earth's atmosphere being opaque to X-rays it is difficult for the observatories on Earth to detect sources emitting X-rays. Before the Uhuru satellite X-ray investigations were conducted employing rockets and balloons, and the number of known X-ray sources was small. During Uhuru flight 339, cosmic X-ray sources were observed (Forman et al., 1978). After the completion of the Uhuru mission new X-ray satellites were launched e.g., Copernicus, ANS, Ariel, OSO7, SASS). New edge instrumentation and the latest techniques of observation have led to the discovery of multiple numbers of X-ray sources. As of now across the universe, thousands of these objects have been detected. The X-ray observatories such as XMM-Newton, and CHANDRA are highly successful in attaining their objective due to the very high resolving capacity of Cameras, Spectrometers, and Telescopes installed therein (Jansen et al., 2001; Turner et al., 2001; Parels & Kahn, 2003). The High-Resolution X-ray observatories in space (such as XMM-Newton), enhance the possibility of detecting and analysing both absorption and emission lines in Galactic X-ray binaries.

In the present work, we have chosen neutron star soft X-ray transients as background sources. Soft X-ray transients are a special class of Low Mass X-ray Binary that radiates X-rays of varying luminosity ranging from 10^{36} - 10^{38} erg s^{-1} (during outburst) to 10^{32} - 10^{33} erg s^{-1} (during quiescence) with soft thermal component below 2 keV and hard component above 2 keV (Coti Zelati, F. et al., 2018; Campana, S. et al.,1998). They allow the investigation of accretion onto compact stars for a much larger range of luminosities and longer periods than persistent sources. This class of LMXB may contain NS or BH as Compact objects. So far around 28 NSSXTs were identified and listed since the first popular catalogue of LMXB was published by Amnuel. (Amnuel, 1978; Amnuel & Guseinov, 1978). The latest catalogue published in the year 2020 comprises 166 LMXBs, out of which 103 are transient (Sazonov et al., 2020; Liu et al., 2007; Ritter et al., 2003; Pakull et al.,1988; Guseinov et al., 2000; Liu et al., 2007; Sidoli et al., 2001) Table 1 comprises of the list of those NSSXTs in which so far absorption lines/edges were detected.

2.2 Probable Sources of Origin of Absorption Features:

The emission lines are linked with the source themselves (Cottam et al., 2001a, 2001b), but that is not always the case with the absorption lines (Cackett et al., 2008). Absorption features seen in an X-ray spectrum may arise due to any of the following reasons-

I. It may be due to an instrumental effect (Rodes-Roca et al., 2014).
II. It may be associated with the source if they are observed to be variable and/or blue-shifted (Lee et al., 2002; Parmar et al., 2002; Ueda et al., 2004; Boirin et al., 2005; Trigo et al., 2006; Miller et al., 2006a, 2006b).

III. It may be due to X-ray dipping phenomena caused by the highly inclined sources. (Sidoli et al., 2001; Parmar et al., 2002; Boirin et al., 2005; Church et al., 2005; Trigo et al., 2006).

IV. It may be due to the ISM in the line of sight, if the absorption lines detected are weak and there is no evidence of a significant blue shift. (Futamoto et al., 2004; Yao & Wang, 2005; Juett et al. 2006).

2.2.1 Absorption Line Due to an Instrumental Effect:

If the absorption feature seen in the spectrum is due to an instrumental effect it might be due to poor calibration. So, a careful comparison of the observation (in which absorption feature is seen) is done with the observations used by the XMM-Newton cross calibration (XCAL) archive. The archive comprises of ∼150 observations of different sources, best possibly reduced, and fitted with spectral models. We also need to check whether the absorption feature is larger than the typical systematic uncertainties in this energy range because for on-axis sources systematic calibration uncertainties are better than 5% in the determination of the total effective area for each Electron Photo Imaging Camera (EPIC) of XMM-Newton[1] in the energy range from 0.4–12.0 KeV. We further need to check whether the equivalent width is higher than the calibration uncertainties or is there any deviation from the calibration accuracy. If so the line will be resolved and cannot be of instrumental origin. (Rodes-Roca et al., 2014).

2.2.2 Absorption Line Associated with The Source:

If the absorption feature is intrinsic to the source, it could be due to any of the following reasons. Absorption features local to the source often appear to be blue-shifted, which points to a disk-wind or generally out-flowing, photoionized plasma. The timing and spectral study of AXJ1745-2901 with Suzaku by Hyodo, Y. et al., 2009 observed four absorption lines at 6.6, 6.9, 7.8, and 8.1 keV, and all of these are due to disk corona because these features found in every orbital phase.

Sanwal et al., 2002 and Liu et al., 2006 suggested that the absorption features may be originated due to energy level transitions of once-ionized helium ions in the strong magnetic field on the surface of the neutron star or they may be due to electron or proton cyclotron absorption lines in an intense magnetic field.

Similarly, Rajagopal et al., 1997; Mereghetti et al., 2002 suggested that these may be due to atomic transitions in some magnetized iron atmospheres or they may be due to transitions of hydrogen-like O/Ne ions in the stellar atmosphere with a strong magnetic field (Mori & Hailey, 2006). Recently Xu et al., 2012 have suggested that the absorption lines could be explained in the framework of the hydro-cyclotron oscillation model. Thus, the observed feature may be a cyclotron line produced in a strongly magnetized neutron star atmosphere or it is an atomic line formed in the neutron star atmosphere.

If an absorption line is formed locally, in the binary system then it must be either in the stellar wind or in the atmosphere of the neutron star. The 2.1 KeV absorption line detected in 4U 1538-52 is an example of such an absorption line. (Rodes-Roca et al.,2014).

A few other examples of absorption lines local to the source are the iron K absorption lines that have been discovered in GX 13+1(Ueda et al.,2004; Sidoli et al., 2002), MXB 1659-298 (Sidoli et al., 2001) and X1624-490, (Parmar et al., 2002).

2.2.3 Absorption Line Associated with X-Ray Dipping Sources:

An irregular decrease in flux occurring at every orbital cycle in the case of many high-inclination (i.e. close to edge-on) low-mass X-ray binaries (LMXB) is called a "dip". To date, only 13 LMXBs hoisting a neutron star (NS) and 6 LMXBs hosting a black hole have shown clear dips in their light curves (D`Ai, A. et al., 2014). Out of these thirteen following five LMXB (EXO 0748-676, MXB1659-298, XTE J1710-281, AX J1745.6−2901, 1A 1744-361) are transient (Table 2.1). Among them, MXB 1659-298, EXO 0748-676 and AX J1745.6-2901 are unique, they exhibit the eclipse, dips, and absorption lines as well.

Table 2.1: List of NSSXTs in the spectra of which absorption line or absorption edge were reported.

Sr. No	Source	Type of the source	Absorp-tion Line/edge	Elements	Nature of origin	Reference
1	4U 1908+005 (Aql X-1)	NSSXT	Y	Ne II, Ne III, Ne IX, Fe L2, Fe L3, O VIIβ, O VIIIα, O I O II, O III, O VIIα	Absorption lines are due to ISM	Pinto et al., 2012
2	GS 1826-238	NSSXT	Y	O I, O II, O VII, Fe I L2, Fe I L3, Ne II, Ne III, Ne K-I, Ne IX, Mg K-I	Absorption lines are due to ISM	Pinto et al., 2010
3	SAX J1808.4-36.58	NSSXT	Y	Ne II, Ne III, Ne IX, Fe L2, Fe L3, O VIIβ, O VIIIα, O I, O III, O VIIα	Absorption lines are due to ISM	Pinto et al., 2012
4	AX J1745.6-2901	NSSXT	Y	Fe XXV Kα, Fe XXVI Kα, Complex of (Fe XXV Kβ, Ni XXVII Kα) and Complex of (Fe XXVI Kβ, Ni XXVIII Kα)	Absorption lines are due to disk corona	Hyodo, Y. et al., 2009

Sr. No	Source	Type of the source	Absorp-tion Line/edge	Elements	Nature of origin	Reference
5	1A1744-36	NSSXT	Y	Fe XXVI	Absorption lines are due to disk corona	Gavriil et al., 2012
6	MXB 1659-298	NSSXT	Y	O VIII 1s-2p, 1s-3p, 1s-4p; Ne X 1s-2p; Fe XXV 1s-2p, Fe XXVI 1s-2p	Absorbing material most likely loacted above and below the accretion disk	Sidoli et al., 2001
7	EXO 0748-676	NSSXT	Y	Ne X Lyα, Ne XI Lyα, O VIII Lyα, O VII He like, N VII Lyα	Absorption lines are due to disk corona	Cottam et al., 2001
8	GRS 1747-312	NSSXT	Y	H like Fe and Ni or mixture of Fe and Ni	Bound-Bound transition of metals	Li, et al., 2018
9	EXO 1747-214	NSSXT	Y	Fe	Surface of the Neutron star/Local to the source	Magnier et al., 1989
10	XB 1916-053	NSSXT	Y	Fe XXV Kα, Fe XXVI Kα, Fe XXV Kβ, Fe XXVI Kβ, O VIII K edge	Absorption lines are due to disk corona	Gambino et al., 2019
11	GX13+1/ 4U 1811-171	NSSXT	Y	Fe XXV; Fe XXVI Kβ; Ni XXVII, Ni XXVIII kα	Absorption lines are due to disk corona	Sidoli et al., 2002
12	4U 1820-30	NSSXT	Y	Ne II, Ne III, Ne IX, O VII, O VIII	Absorption lines are due to ISM	Cackett et al., 2008

The spectral changes observed during a dipping activity in LMXB are not that simple and cannot be reproduced by simple absorption with neutral materials. In the literature, two physical attributes are largely discussed to explain the occurrence of dips namely the azimuthal-dependent height of the accretion disk's outer rim and a large system-inclination angle (White & Holt, 1982). Depending upon the orbital phase, our line of sight is partially or completely intercepted by the rim causing local absorption of X-rays produced in the innermost parts of the system. Contemporarily Frank et al.,1987 proposed a different view partially able to explain many observed facts like the periodic occurrence of dips, the dependence on the orbital phase, and the duration and time scales of the single dips. A two-component model consisting of a compact blackbody and an extended power law has succeeded in explaining the dip and persistent spectra (Parmar et al.,1986; Bałuci´nska-Church, 1995; 1997). During dip the compact component is heavily absorbed on the contrary the extended component is gradually absorbed as increasing dip flux. Based on the two-component model, Boirin et al., 2005, and D´ıaz Trigo et al., 2006) proposed an alternative interpretation that the spectra can be simply explained using the updated photo-ionization code.

There are many other neutron star X-ray binaries (we restricted ourselves to NSSXTs) in which the nature of the absorption lines observed is less clear, the lines are weaker and there is no evidence of significant blue shifts, supporting the conclusion that these lines may be due to the interstellar medium. The absorption lines caused due to ISM are discussed elaborately in the next section.

2.2.4 Absorption Line Associated with Ism:

The interstellar medium (ISM) has a multiphase structure comprised of gas, dust, and molecules. The gas can be found in different charge states: neutral, weakly ionized (warm), and highly ionized (hot) (Table 2.2).

Table 2.2: Different Phases of ISM and their Characteristics

Phase of ISM	Components in a Phase	Heating/ionizing sources	Molecules found	The temperature of Phase(K)	Column density, nH (cm^{-3})
Cold	Molecules	Starlight, Dust, cosmic rays	H_2, CO, ...	10-20	$10^2 - 10^6$
	Neutral gas	Starlight, dust, cosmic rays	HI, OI, ...	50-100	20 − 50
Warm	Neutral gas	Starlight, Dust	HI, OI, ...	$(5 - 10) \times 10^3$	0.2 − 0.6
		Cosmic rays			
	Ionized gas	UV photons from hot stars	HII, OII–III, ...	~ 8 000	$0.2 – 10^{-4}$
Hot	Ionized gas	Shockwaves from SNe	OVI–VIII, ...	$\sim 10^6$	$(4 – 6) \times 10^{-3}$

(Note: For details, please see Table 1.1 of Pinto. C, 2013)

Nowadays, the study of the X-ray absorption lines in the spectra of background sources become a tool to probe the multiphase ISM through the observation of its absorption lines and edges. The observed K-shell transitions of Low-Z elements, such as oxygen and neon, and the L-shell transitions of iron and the different charge states for each element allow us to constrain the multiphase ISM, i.e. its ionization state and temperature distribution. But the most challenging is still to identify the origin of the absorption lines. If the absorption lines are due to the absorption of energy while crossing the intervening medium i.e. ISM, then those lines must not be blue-shifted. This can be confirmed by comparing the equivalent widths of the absorption lines of various observations. If the equivalent width does not vary between observations, this would indicate that the absorbing column has remained unchanged between the observations, as would be expected for absorption lines associated with the ISM. Since the equivalent width is a direct measure of the absorbing column when the line is unsaturated and on the linear part of the curve of growth. However, if the lines are saturated, then even if the column density changes significantly (for instance in response to changes in the source) the equivalent width would remain more or less constant. Figure 2.1 is the Spectra of two observations, Obs. Id. 6633 and 6634, of the NSSXT source 4U1820-30. It shows various absorption lines caused due to ISM on the LOS (Cackett et al., 2008).

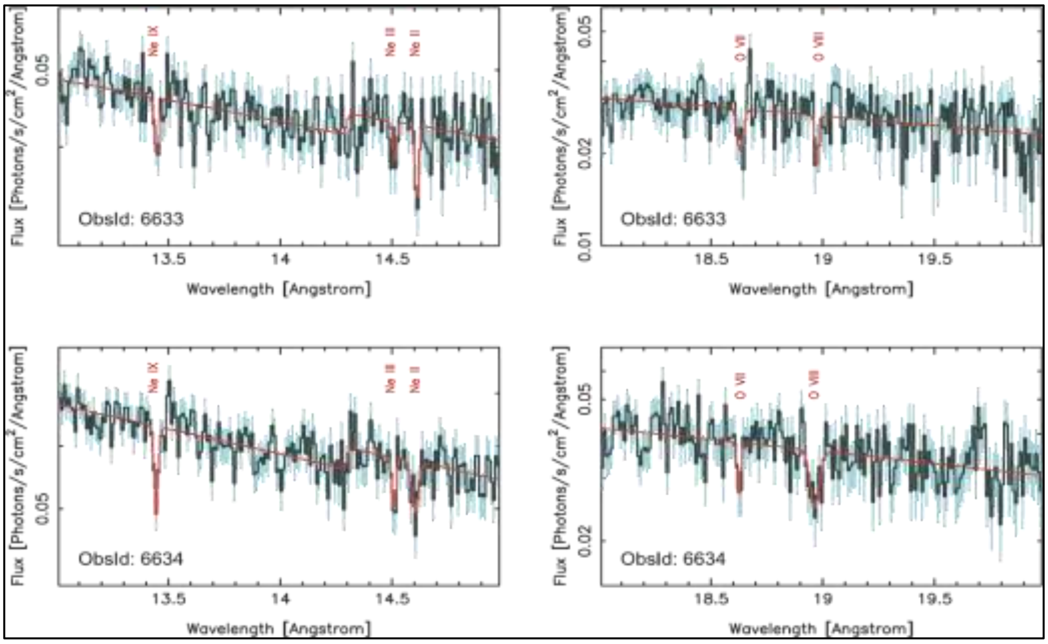

Figure 2.1: The top panels show absorption in Obs ID 6633, and the bottom panels show absorption in Obs ID 6634. The data are in black, and the error bars are in blue. The best-fitting model is in red. The continuum is fit by a power law modified by neutral ISM absorption edges, where appropriate. Absorption lines are modeled by a Gaussian. (reproduced by permission of the AAS: Figure 1 from "Investigating the Nature of Absorption Lines in the Chandra X-Ray Spectra of the Neutron Star Binary 4U 1820–30 E. M. Cackett *et al* 2008 *ApJ* 677 1233) (doi **10.1086/529483)**

As summarized in Table 2.2 (Pinto. C., 2013) in many spectral analyses the cause of absorption lines observed is found to be due to ISM. In a series of such studies, the study carried out by Juett et al., 2004 can be considered to be the first dedicated study of ISM. 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: OII / OI ≈ 0.1 and OIII / OI ≤ 0.1. They also estimated the velocity dispersion of the neutral lines to be 200 km s^{-1}, which suggests that the absorption lines originate in the ISM rather than in a circumstellar environment local to the binaries. Likewise, Futamoto et al., 2004 after spectrum analysis, clearly detect the OVII

Kα, OVIII Kα, and OVII Kβ lines and NeIX Kα absorption lines in the LETG spectrum. From their curve-of-growth analysis and photoionization modeling, they deduce that all oxygen will be fully photoionized if the absorbing column is located close to the binary system, and therefore attribute these lines to hot gas in the ISM. A similar observation was also obtained by Paerels et al., 2001 when they were trying to probe emission lines intrinsic to the LMXB 4U 0614+09. They did not find any of those lines but detected K-shell absorption by interstellar O and Ne and L-shell absorption by Fe. From a study of 10 (Ten) low-mass X-ray binaries, Yao &Wang, 2005 find that the detected NeIX, OVII, and OVIII absorption lines are consistent with the hot ISM origin.

In continuation of their studies, Juett et al., 2006 extended the analysis to the Ne and Fe edges and measured interesting abundance ratios: O/Ne = 5.4±1.6 and Fe/Ne = 0.20 ± 0.03. They found that 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. In the same year, Yao & Wang, 2000 came up with the measurement of column densities of oxygen and their abundances on a broad range of ionization states (by comparing their oxygen column densities with the hydrogen measurements at 21 cm).

Lee et al., 2009 successfully applied the proposal made by Lee & Ravel, 2005 to use the iron absorption edges to determine the quantity and composition of interstellar dust. Lee et al., 2009 applied this idea in Chandra/HETGS observations of the X-ray binary Cygnus X-1 and found evidence for hematite and iron silicates. Later in the year 2012, Costantini et al., 2012 combined Chandra and XMM-Newton spectra of the bright LMXB 4U 1820-303 and found that the dust provides about 20% of oxygen and 90% of iron.

2.3 Conclusion:

Absorption spectroscopy has evolved as a great diagnostic tool for studying the physical and chemical composition of the constituents of LMXBs as well as ISM. In this context, the X-ray transient sources play a crucial role because of their wide variation of luminosity, ranging from 10^{36} -10^{38} erg s^{-1} (during Outburst) (Coti Zelati et al., 2018) to 10^{32}– 10^{33} erg s^{-1} (during quiescence) (Campana et al.,1998) exponential decay of the luminosity extending over many decades. Thus, they allow the investigation of accretion onto compact stars for a much larger range of luminosities and longer periods than persistent sources. The role of powerful telescopes, Spectrometers in space observatories like Integral, Chandra, XMM-Newton, Swift, etc. is equally important as we could defy the opacity of X-ray due to Earth's atmosphere and study various types of X-ray binaries and their spectra. Because of the High-Resolution X-ray Spectrometers onboard, it becomes possible of evaluating metal abundances in ISM via absorption spectra. It is generally difficult to ascertain the cause of the origin of absorption lines and we tried to summarize all probable causes of absorption observed in the spectra and how to identify them.

Although the spectral resolution and sensitivity of the currently available X-ray telescopes are limited for detecting absorption features due to the least abundant element, persistent efforts are going on to improve the resolution capacity further.

Exertions are on to address issues like the detection of new SXTs, finalizing the structure of the accretion disk, evaluating the origin of X-rays from various regimes, the composition of NS, evaluating the composition of ISM, etc.

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