Progression of X-ray astronomy and its significance in understanding Neutron Star Soft X-ray Transient

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**ABSTRACT**

 Soft X-ray transients are one of the many varieties of Low Mass X-ray Binaries (LMXB), which typically radiate in a latent state with very low luminosity but on rare occasions outgo sporadic outbursts with a 100-1000 times increase in its luminosity. Out of 166 LMXB, 30 have so far been classified as Neutron Star Soft X-ray Transients (NSSXT) with spatial distribution│l│= ±10 deg and │b│ < 20 deg. In this paper, we attempt to summarise the role of High-resolution X-ray Spectroscopy(HRXS) and models conceived in evaluating various activities exhibited by NSSXTs during X-ray emission, particularly the process of X-ray emission during outburst and quiescence states and thereby how our understanding of the Physical and Chemical structure of NS comprising NSSXTs has evolved. The Choice of NSSXT is significant because in SXT X-ray emission during quiescence in principle is because of the mechanism without inflow of matter into the primary star.

**Keywords:** HRXS, NSSXT, Model, LMXB, Quiescent, Outburst

#  INTRODUCTION

 It was always challenging to study the supranuclear degenerate matter surrounding the neutron star (Bhattacharya et al., 2010). Efforts were consistently put forth by various groups and individuals to study this matter because of the wide possibility of revealing many new insights about neutron stars, the core collapse of massive stars and also to gather information about the phenomenon of supernovas (Van Kerkwijk, 2004). It is next to impossible to obtain such matter in a laboratory which makes these studies highly significant and unparalleled. The X-ray radiation from neutron stars and nearby atmosphere contains information about the matter around the neutron star (NS) and these pieces of information can be derived from the timing and spectral analysis of these X-ray emission. The High-resolution X-ray Spectroscopy (HRXS) evolves as a powerful tool in this direction. 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. High-resolution X-ray Spectroscopy (HRXS) has turned up as a sustainable diagnostic tool for evaluating the chemical and physical properties of the NS, the atmosphere near it and 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 journey of X-ray astronomy is not too old; it starts with the discovery of Scorpius X-1 (SCO X-1) by Giaconni et al. in the year 1962 and presently we have a sea of data because of the launching of a series of dedicated astronomical study satellite starting from the first X-ray satellite Vela launched in 1963. X-ray astronomy opened up a new dimension of understanding the universe, its dynamics, and various governing phenomena. New edge instrumentation and advanced technical tools of observation have paved the path to the detection of multiple numbers of X-ray sources. Since the Earth’s atmosphere prohibits X-rays from reaching the surface of the Earth. Thus observatories on Earth are unable to study a good chunk of the electromagnetic spectrum and are devoid of the information carried by X-rays originating at neutron stars and its nearby area. This problem was resolved by setting up X-ray observatories outside the Earth’s atmosphere. The launching of satellites equipped with X-ray detectors on-board started in the year 1963 with the launching of the satellite named Vela. Since then more than 50 (fifty) satellites have already been commissioned up to 2022. The major upcoming projects are XPoSat, XRISM, ASTROSAT2, ATHENA etc. The most popular among them are - XMM Newton of the European Space Agency (ESA); Rossi X-ray Timing Explorer (RXTE) of the National Aeronautics and Space Administration (NASA); Suzaku of the Japan Aerospace Exploration Agency (JAXA); NASA’s Chandra and ASTROSAT of Indian Space Research Organisation. Since X-ray emission is associated with different phenomena such as Thermonuclear bursts, and Kilohertz quasi-periodic oscillations (KQPO) apart from the continuum energy spectrum, therefore variety of instruments such as Proportional Counter Array or PCA, Reflection Grating Spectrometer or RGS etc. were designed and installed to acquire X-rays according to the demand. The large photon collecting area and time resolution of ~11s turned out The PCA (installed in RXTE) to be the ideal tool for studying fast-timing phenomena such as KQPO (Bhattacharya et al., 2010). However, its poor energy resolution limits its capacity to study the spectral lines. The XMM Newton satellite and Chandra resolved this problem to a great extent and turned out to be ideal for detecting and analysing closely spaced spectral lines (in the 0.1–12 keV range). The high-resolution “Reflection Grating Spectrometers (RGS)” on-board XMM-Newton and the “Low Energy Transmission Grating (LETG)” and “High Energy Transmission Grating (HETG)” spectrometers in CHANDRA help them to do so. The XMM-Newton and Chandra play an appreciable role in the study of the quiescent emission of neutron star Low Mass X-ray binaries (LMXB). Likewise, the satellite Suzaku with the help of the “Hard X-ray Detector” (HXD) on board, facilitates the study of the broadband energy spectrum by detecting the broad relativistic iron emission lines (Bhattacharya et al., 2010). The “Large Area X-ray Proportional Counter (LAXPC)" installed in ASTROSAT (launched in the year 2015) is capable of measuring hard X-rays (~50keV) high-frequency timing features and accretion-powered pulsations.

 To date, in the universe, thousands of X-ray emitting sources have been detected, We restricted ourselves to the LMXBs, particularly to the neutron star soft X-ray transients (NSSXT) in this review. Such LMXB sources are outstanding test beds for a wide range of astrophysical queries and analysis of fundamental physics. Observations of neutron star LMXBs can also help constrain the equation of state of matter at supranuclear densities. These sources also help in testing theories, such as “Einstein’s theory of general relativity”, in the strong field regime. The Soft X-ray transients are a special class of Low Mass X-ray Binary which radiates X-ray of varying luminosity ranging from 1036 -1038 erg s-1 (during outburst) (F.Coti Zelati et al., 2018) to 1032–1033 erg s-1 (during quiescence) (S. Campana et al.,1998) with soft thermal component below 2 keV and hard component above 2 keV. The Several orders of luminosity variation in transient binaries is a common practice. These variations reflect, at least partially, the change of the matter inflow rate toward the primary object and generate an opportunity to sample a variety of physical conditions and regimes that are inaccessible to persistent (bright) sources. SXRTs in the state of quiescent are most interesting because X-ray emission mechanisms during quiescence do not involve the inflow of mass onto the compact star (neutron star) surface (S. Campana & L. Stella, 2003). It may help us to understand what causes the accretion onto the primary object in SXTs to be intermittent, This may reveal the strength of magnetic intensity and rotation period of the compact star (neutron star) at low accretion rates. The field strength and period thus obtained may then be compared with the field strength and period of the recycled radio pulsars with low-mass white-dwarf companions. (Frank Verbunt, 1996)

 So far around 30 NSSXTs have been detected since the first popular catalogue of LMXB was published by P.R.Amnuel et al. in the year, 1979. The most latest catalogue published in the year 2020 comprises 166 LMXBs, out of which 103 are transient. In this paper, we attempt to summarise the contribution of High-resolution X-ray Spectroscopy (HRXS) and models conceived in evaluating various activities exhibited (Particularly the process of X-ray emission during outburst and quiescence states) by NSSXTs during X-ray emission. Further, we attempt to summarise the outcomes of the Physical and Chemical structure of NS comprising NSSXTs. The Choice of NSSXT is significant, because in SXT X-ray emission during quiescence in principle is in the absence of of inflow of matter into the primary star.

# SOURCES OF X-RAYS

 It is now more than six decades since the Sun was identified as the first celestial object to give off X-rays from its outer atmosphere in 1949 detected using rocket-borne radiation counters. It is an essentially weak X-ray source. At present, we know various categories of X-ray radiating sources such as Seyfert galaxies, Quasars and Radio Galaxies. The Clusters also emit the X-rays but these do not come from their member galaxies but rather from a pool of hot gas between them. However, the X-ray binary stars are among the prominent X-ray-emitting sources. They radiate 1,000 times as great as the Sun’s radiation at all wavelengths and therefore in this review our focus is NSSXT, one of the types of Low Mass X-ray binary. The most latest catalogue published in the year 2020 speaks about 166 LMXBs detected in Milkyway, out of which 103 are transient (Q.Z. Liu et al., 2007).

 The Catalogue published by Q.Z. Liu et al. in the year 2007 showed a consistent growth in the number of LMXB in Large Magellanic Cloud (LMC) because of the constant development and deployment of the sensitive telescopes, spectrometers and launching of new survey missions. The comparison of mass between the Galactic centre and LMC tells that the availability of LMXB in LMC appears to be comparable to that in the Milky Way. (S. Sazonov et al., 2020). However, to date, only a few LMXBs were confirmed like LMC X-2 (Grebenev et al., 2013), 3FGL J0427.9-6704 discovered by Fermi (Strader et al. 2016), LHG 83 and LHG 87 (M.W.Pakull et al., 1987). A.P. Cowley et al. in the year 1997 predicted that there would be ~ 1-2 dozen of LMXB in LMC. X-ray binaries were also detected in NGC 720 (Jeltema et al., 2003) and NGC 1399 (Angelini et al., 2001). Barnard et al., 2003, even discovered a Z-source Low-Mass X-ray Binary, RXJ0042.6+4115, in M31. Most of the ultra-luminous X-ray sources in elliptical galaxies (Liu & Mirabel, 2005) are believed to be LMXBs with a black hole. Till now 57 faint X-ray sources and 13 LMXB with neutron stars as compact stars are known in the Galactic globular cluster systems (Verbunt, 2001). Some of these were believed to be quiescent LMXBs (qLMXBs) containing neutron stars (Verbunt et al, 1984). Many such quiescent low-mass X-ray binaries were also detected by the Chandra and XMM-Newton observations in several globular clusters (e.g. NGC 6440, Heinke et al., 2003). These LMXBs, however, have not been included in this catalogue. The stellar mass of the Small Magellanic Cloud (SMC) is just 1/10th of that of the LMC (Van der Marel et al., 2009) and maybe because of that, no LMXBs have been found in SMC.

1. **X-ray transients**

 An X-ray binary system is broadly categorised into High Mass X-ray binary (HMXB) and Low mass X-ray binary (LMXB). In HMXB the compact star is a strongly magnetized neutron star (NS) while in the case of LMXB, it is either a neutron star (NS) or a black hole (BH). Again, the secondary star in the case of HMXB is a very massive O or B-type star while in the case of LMXB, the secondary star may be a white dwarf, late-type sequence star, F-G type subgiant star, or A-type star. The LMXB is additionally divided into two groups Z-track LMXB and Atoll LMXB (Hasinger & Van der Klis, 1989). The majority of the LMXB is Atoll sources. As per Liu's 2007 catalogue, there are 150 LMXB out of which Atoll source 18, X-ray burst source 63, Dipping LMXB 11, Globular cluster X-ray sources 13, X-ray pulsar 15, transients X-ray sources 76, Z type 7 etc. A single LMXB may fall into two or three of the above categories.

 The transient X-ray sources are a special class of LMXB that remain dormant and undetected for the majority of the time and undergo sporadic outbursts. The sudden outbursts typically last for 10 to 100 days and then fade into invisibility. Their high luminosity (1037 to 1038 erg s-1), (F.Coti Zelati et al., 2018) time variability all through outbursts and optical counterparts are similar to the persistent bright X-ray sources. These are also similar to close binary systems powered by the accretion of mass onto a compact star. Transient systems are important because the luminosity of these classes of binaries varies over many decades; thus they allow to investigate accretion onto compact stars for a much larger range of luminosities and therefore accretion rates, than persistent sources. Further, the transient LMXBs are categorised into three groups- Hard X-ray transients (HXRTs/ HRTs) Soft X-ray transients (SXRTs/ SXTs) and Ultra Soft X-ray transients (USXT).

HXRTs are typically connected with persistent X-ray pulsars in HMXBs and typically comprise a young, pulsating neutron star circling a Be star companion. SXRTs, on the other hand, are close binary systems in which a compact object is either a black hole or a neutron star that quickly and efficiently absorbs mass from a low-mass companion, a lower main sequence star, or a (sub) giant star (J.P.Lasota, 1996).

The transient X-ray source population has also been identified in Magellanic-type galaxies such as the Small and Large Magellanic Clouds (SMC and LMC) and NGC 55 (Kahabka & Pietsch, 1996; Coe et al., 2001; Jithesh & Wang, 2016, and references therein).

1. **Soft X-ray Transients ( SXT/SXRTs):**

As implied by its name, the "Soft X-ray Transient" emits the majority of its outburst energy in soft (a few KeV) X-rays (J.P.Lasota, 2001). A Pronounced increase in the luminosity of their (faint) optical counterparts and the onset of type-1 bursts associate SXRTs with LMXBs containing an old neutron star. Typical SXTs are generally very faint or even remain latent in X-rays. This state is called the "quiescent" state (S.Campana et al., 1998 ). The SXTs have outbursts with a recurrence time of 60-350 days (Simon Vojtech, 2004). The system again returns back to quiescence in a few months. The probable mechanism of this dwindling between outbursts and quiescence state is explained in section 3.1.

During the outburst, the X-ray luminosity of an SXT can rise by a factor of 100 –10,000. Whether you consider the peak intensity Imax of the individual outbursts or the outburst-to-outburst variations of Imax are highly variable (Simon Vojtech, 2004). Most SXTs exhibit a rapid ascent (~a few days) followed by a slower descent (about 30 days), with the X-ray light curve rebrightening about 20 days after the maximum, as illustrated in Fig. 1. It is also observed that during outburst the optical output of the secondary star also rises by about 4-7 magnitudes, depending on the size of the star. There is a special group of SXTs that has several years-long outbursts before they return to quiescence. These quasi-persistent SXTs act as an ideal testing ground because of their prolonged outbursts, which heat the neutron star crust to a temperature greater than the neutron star core, Contrary to that, the X-ray luminosity released during quiescent state provides data on the cooling properties of the neutron star (Brown, Bildsten & Rutledge, 1998; Colpi et al., 2001; Wijnands et al., 2001; Rutledge et al., 2002; Cackett et al., 2006a).

 When a transient LMXB goes into an outburst, the system's accretion rate increases, and the accumulated in-falling matter is heated up and emits X-rays (e.g., Shakura & Sunyaev 1973). Not all of the in-falling material ends up on the central object, however, some fraction is expelled from the system. In some cases, a jet is formed. (N.V. Gusinskaia et al., 2017 ).Thus An SXRT always shows the following two characteristics:

(1) When the source goes back to quiescence, the accretion rate is reduced by several orders of magnitude and

(2) During outburst the spectra become soft.

The graph proposed by King and Ritter-1998 shown in Fig. 1 represents an SXT schematically.



**Fig. 1: Schematic representation of an SXT outburst according to King & Ritter-1998 model (This figure is taken from the paper published in MNRAS by A.R. King and H. Ritter, 1998)**

Among the 30 NSSXTs identified and tabulated (Table 1), Aql X-1 is observed to be the most active NSSXT, more than 30 X-ray and/or optical outbursts have been so far detected. This paved the way to correlate the characteristics of various eruptions and to trace out possible (quasi) periodicities in the recurrence times. A cycle of ~ 125 d was quite evident in the 1969–1979 observations from the Ariel V and Vela 5B satellites while recent Ginga and Optical observations (1987-1992) on the contrary suggest a ~310 d periodicity. The analysis presented by Vojtech Simon of Czech Republic in the 5th Integral Science Workshop, 16-20 February 2004 shows that the cycle of outbursts is 60-350 days, which means up to 19 bursts have been witnessed in some of them (Vojtech Simon, 2004). It is also clear that the cycle of outburst for SXTs containing black holes is longer than in SXTs containing neutron stars.

 Van Paradijs (1984) draws an analogy between SXT and dwarf novae. Dwarf novae super outbursts tend to have larger amplitudes and a longer duration than the normal ‘U Gem-type’ outbursts. Dwarf novae are similar to SXT in many respects (J.P.Lasota, 2001). The discs during an outburst in dwarf novae and SXTs are nearly alike except for the fact that the discs in the SXTs are heavily irradiated by the central X–ray source (Van Paradijs & McClintock, 1994; Shahbaz & Kuulkers, 1998). In a paper (King & Ritter, 1998), King and Ritter note that irradiation prolongs the entire cycle of the SXT outburst, causing the SXT light curve to have long tails (exponential or linear) since the outburst can be shut off only by the viscus decay of central accretion rather than through a cooling front (as is the case with dwarf novae).

 The Catalogue accounts for 103 transient X-ray sources of which approximately 75% have BH as compact objects and 25% have NS as the compact object. (Catalogue of Liu, 2001) Thus around 25-30 sources can be NSSXTs. It is also seen X-ray transients with NS are generally SXTs. (Table 1**)** contains the list of confirmed NSSXTs and their location. To prepare Table 1, we have consulted, the papers of S. Campana et al. (1998), Q.Z. Liu et al. (2001) and Y.X. WU et al.(2010), along with others mentioned in the reference column. Fig. 2 shows the spatial distribution of NSSXTs as shown in Table 1.The graphshows that these are concentrated mostly within latitude ± 20 deg, galactic plane region. While the following NS SXTs 1H 1905+000 (l, b = 35, 3.7), XTE J2123-058 (l, b = 58.1, - 9.0), XTE J 0929-314 (l, b = 260.1, 14.21), EXO 078-676 (l, b = 280, 19.3) & 4U 1456-32 (l, b = 332.2, 23.9) has exception and spread up to ± 30 deg. The previous missions support these observations (Gursky and Schreier, 1975; Skinner, 1993; Grebenev et al., 1996; Grimm et al., 2002). The increasing size of the catalogue of INTEGRAL it is becoming more vivid than the concentration of HMXBs seen in spiral arm tangents and LMXBs towards the Galactic Centre.( Dean et al., 2005; Bodaghee et al., 2007; Krivonos et al., 2015).

**Fig. 2 Spatial distribution of NSSXTs**

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| **Table 1: Summary of all the NSSXTs so far reported in various catalogues and Papers** |
| Sl. NO. | Source | List of Soft X-ray Transients as per S Campana et al.-1998 | Type of the source as per Liu et al.-2001 | List of Transients type as per Wu et al .-2010 | Based on Papers mentioned in the reference apart from S. Campana et al., Liu et al. and Wu et al. | Year of Outburst Wu et al. 2010 & S. Campana 1998) | RA and Dec | Longitude and Latitude, Liu, 2001 Galactic Co-ordinate | Dist (Kpc) \* Campana | Luminosity during outburst and quiescent (erg per Sec) ( see Campana) | Porb (hr) | Referenece |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 4U 1456-32 (cen X-4)/ 1455-314 (Liu) | B-0 | TB | NS(B) | X | 1969, 1979 | 14 55 19.6, -31 28 09 | 332.2, +23.9 | 1.2 | 35.5-32.5 | 15.1 (C,W) | X |
| 2 | 4U 1908+005 (Aql X-1) | B-O-Q | TBA | NS(B) | X | 1978 Recurrent (C) | 19 08 42.8 +00 30 05 | 35.7 -4.1 | 5 (W), 2.5 | 36-32.8 | 18.95 (W) 18.9 (C) | X |
| 3 | 4U1608-52 | B-O-Q | TBA | NS(B) | X | 1976, Recurrent (C) | 16 08 52.2, -52 17 43 | 330.9 -0.9 | 3.5 | 36-33.3 | 12.89(W) | X |
| 4 | AXJ 1745.6-2901 | X | TB | NS(B) | X | 1996 | 17 45 36 -29 01 34 | 359.9 -0.035 | > 8 kpc \* | X | 8.4 ( W ) | \* (Ponti et al. 2017; Jin et al. 2017). |
| 5 | EXO 0748-676 | B-O | TBD | NS(B) | X | 1985 Recurrent (C ) | 07 48 25.8 -67 37 32 | 280.0 - 19.3 | 5.9-7.7 (W) 10 | 36-34 | 3.8 | X |
| 6 | GRS 1747-312 | X | GT | NS(B) | X | 1990, 1996-1999 | 17 47 31.2 -31 16 45 | 358.6 -2.2 | 9.5 (W) 13 | 36.5 | 12.36 (W) | X |
| 7 | GS 1826-238 | X | TB | NS(B) | X | 1988 Recurrent | 18 26 24 -23 49 31 | 9.3 -6.0 | 4-6 | X | 2.08 (W) | X |
| 8 | HETE J 1900.1-2455 | X | X | NS(B) | X | 2005 | 19 00 08.65 -24 55 13.7 | 11.30 -12.87 | 5 (W) | X | 1.39(W) | X |
| Sl. NO. | Source | List of Soft X-ray Transients as per S Campana et al.-1998 | Type of the source as per Liu et al.-2001 | List of Transients type as per Wu et al .-2010 | Based on Papers mentioned in the reference apart from S. Campana et al., Liu et al. and Wu et al. | Year of Outburst ( Wu et al. 2010 & S. Campana 1998) | RA and Dec | Longitude and Latitude, Liu, 2001 Galactic Co-ordinate | Dist (Kpc) \* Campana | Luminosity during outburst and quiescent (erg per Sec) ( see Campana) | Porb (hr) | Referenece |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 9 | 1A1744-36 | X | T | NS(B) | X | 1976, 1989, 2003, 2004, 2005 | 17 44 50.9, -36 06 54 | 354.1, - 4.2 | < 9 (W) | X | 1.62 (W) | X |
| 10 | IGR J 00291+5934 | X | X | NS(MP) | X | 2004 | 00 29 03.06 +59 34 19.0 | 120.09 -03.17 | 2.6-3.6 (W) | X | 2.46 (W) | X |
| 11 | MXB 1659-298 | B-O | TBD | NS(MP) | X | 1976, 1978, 1999 | 16 58 55.4 -29 52 28 | 353.8 +7.3 | 10 (W) | 36 | 7.2 ( C ) | X |
| 12 | SAX J1808.4 -36.58 | B | TPB | NS(MP,B) | X | 1997,1998, 2000,2002, 2005, 2008 | 18 08 27.54 -36 58 44.3 | 355.4, -8.14 | 2.5/3-4-3.6 (W) ~4 (C ) | 36.3 | 2.014(W) | X |
| 13 | XTEJ 0929-314 | X | X | NS(MP,B) | X | 2002 | 09 29 20.19 -31 23 03.2 | 260.10 +14.21 | 10 ± 5 (W) | x | 0.73 | X |
| 14 | XTEJ 2123-058 | X | TBA | NS(MP,B) | X | 1998 | 21 23 14.54 -0547 52.9 | 58.10 -29.9 | 8.5±2.5 (W) | X | 5.96(W) | X |
| 15 | XTEJ 1710-281 | X | TB | NS(MP,B) | X | 1998 | 17 10 12.3 -28 07 54 | 356.4 +6.9 | 12-16 | x | 3.28 (W) | X |
| 16 | XTEJ 1751-305 | X | X | NS(MP,B) | x | 2002 | 17 51 13.49 -30 37 23.4 | 359.18 -01.91 | ~ 8.5/>7 | X | 0.71 (W) | X |
| 17 | XTEJ 1807-294 | X | X | NS(MP,B) | X | 2003 | 18 06 59.8 -29 24 30 | 1.93 -04.27 | X | X | 0.668(W) | X |
| 18 | XTEJ 1814-338 | X | X | NS(MP,B) | x | 2003 | 18 13 39.03 -33 46 22.3 | 358.74 -07.58 | 8±1.6 | X | 4.27(W) | X |
| Sl. NO. | Source | List of Soft X-ray Transients as per S Campana et al.-1998 | Type of the source as per Liu et al.-2001 | List of Transients type as per Wu et al .-2010 | Based on Papers mentioned in the reference apart from S. Campana et al., Liu et al. and Wu et al. | Year of Outburst ( Wu et al. 2010 & S. Campana 1998) | RA and Dec | Longitude and Latitude, Liu, 2001 Galactic Co-ordinate | Dist (Kpc) \* Campana | Luminosity during outburst and quiescent (erg per Sec) ( see Campana) | Porb (hr) | Referenece |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 19 | 4U 2129+47 | B-O | BT | X | NS LMXB | up to 1981 | 21 29 36.2 +47 04 08 | 91.6 -3.0 | 6 (C ) | 36.8-32.8 | 5.2 | Michael R. Garcia and Jonathan E. Grindlay, 1987 |
| 20 | KS 1741-293 | B | TB | X | NS LMXB | 1971 | 17 41 38 -29 19 53 | 359.5 -0.07 | 10 (C) | ~37 | X | N. Degenaar and R. Wijnands, 2012 |
| 21 | EXO 1747-214 | B | TB | X | NS LMXB | 1985 | 17 47 25.7 -21 24 33 | 19.8 +22.73 | 10 (C) | 35.6 | X | J Tomsick et al. 2005 |
| 22 | 1A 1743-288/ SAX J1747.0-2853 | X | TB | X | NS LMXB | 1971, 1976/ 1998, 1999, 2000 and 2001\* | 17 43.9 - 28 52 36 | 0.11 -0.11 | 10 (C) | 37 | X | L Natalucci, A Bazzano, M Cocchi, P Ubertini et al.2000 |
| 23 | KS 1731-260 | X | BT | X | NSLMXB | 1990 | 17 31 06.8 -26 03 10 | 1.1 +3.6 | 7\* | X | X | R Wijnands, M Guainazzi, M van der Klis, 2002… |
| 24 | IGR J 17473-2721 | X | X | X | NST | 2005, 2008 | 17 47 18.06 -27 20 38.9 | 1.55 +0.51 | X | X | X | NS, S. Zhang, Y.-P. Chen, J.-M. Wang, D. F. Torres, Chenevez, D Altamirano and DK Galloway, 2011 |
| 25 | EXO 1745-248 | X | X | X | TGB/ns tran LMXB, | 2000, 2010, 2011 | 17 45 51 -24 52 45 | 3.8 +1.5 | X | X | X | N. Degenaar and R. Wijnands, 2012 |
| 26 | 1H 1905 +000 | X | X | x | B/NSSXT | 2006 | 19 05 53.4 +00 05 18 | 35.0 3.7 | X | X | X | P. G. Jonker C. G. Bassa, G. Nelemans, A. M. Juett, E. F. Brown and D. Chakrabarty, 2006 |
| Sl. NO. | Source | List of Soft X-ray Transients as per S Campana et al.-1998 | Type of the source as per Liu et al.-2001 | List of Transients type as per Wu et al .-2010 | Based on Papers mentioned in the reference apart from S. Campana et al., Liu et al. and Wu et al. | Year of Outburst ( Wu et al. 2010 & S. Campana 1998) | RA and Dec | Longitude and Latitude, Liu, 2001 Galactic Co-ordinate | Dist (Kpc) \* Campana | Luminosity during outburst and quiescent (erg per Sec) ( see Campana) | Porb (hr) | Referenece |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 27 | RXS J170930.2-263927 | X | X | X | NSSXT | 2002 | 17 09 30.2 -26 39 27 | 357.5 +7.9 | X | X | X | P. G. Jonker, M. M´endez, G. Nelemans, R. Wijnands and M. van der Klis, 2003 |
| 28 | MX 0836-42 | B | TB | X | NSSXT | 1970, 1971, 1990, 1991 | 08 35 37 -42 42.6 | 261.9 -1.1 | 10 (C) | 36.5-35 | X | L Stella, S Campana, M Colpi, 2006 |
| 29 | 4U 1735-28 | X | T | X | X | 1971 | 17 35.4 - 28.45 | 359.6 +1.56 | 10 (C) | 36.5 | X |  |
| 30 | MX 0656-07 | X | T | X | X | 1975 | 06 56 01 -07 11.7 | 220.2 -1.7 | 10 (C) | 36 | X |  |

Note: In table 1, (c) stands for Campana et al., 1998 and W stands for Wu et al., 2010.

 The label B indicates SXTs in which the burst occurred, T indicates Transient, O indicates optically identified SXTs, Q indicates kHz QPO and A stands for Aroll.

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# MODELS THAT HAVE HELPED IN UNDERSTANDING SOFT X-RAY SPECTRA EMITTED BY NSSXTS

 Radiations from SXTs during outburst and/or quiescence have now become an exciting and important area of study because the high accretion rate variability of SXTs allows for the study of a range of different regimes of the neutron stars in those systems, which are otherwise inaccessible to persistent LMXBs (S. Campana et al., 1998). So, far we know X-rays are created by the inner accretion disk and/ or the boundary layer due to the impact of the accretion flow with the compact star. (Dacheng Lin et al. 2007).

 There are a whole lot of questions associated with the emission of radiation from SXTs. With time, many propositions have been made, tested and retested. Various physical conditions were measured but still, it is believed that there is a lot many which needs to be established. To understand and explain the range of radiations emitted from various regimes of the accretion disk and NS, several models have been proposed since 1973, the proposal made by N. I. Shakura and R. A. Sunyaev to a paper titled Rotating neutron star (or Pulsar) by Dr Cristrina Baglio and Dr David Russel which claims that it took 12 days for the material to swirl in the ward and collide with pulsar several times longer than astrophysicist expected. (Yet to be published).

So far, several approaches have been developed to elucidate the X-ray spectral profiles of accreting NSs.. These can be broadly categorized as:

1. Spectral surveys of a vast number of sources, across a broad spectrum of luminosities (Church & Baluci´nska-Church 2001; Christian & Swank1997),
2. Detailed analysis of hundreds of observations generated from a single burst of NS X-ray transients (Gierli´nski & Done 2002b; Maccarone & Coppi 2003b; Maitra & Bailyn 2004),
3. Fourier frequency-resolved X-ray spectroscopy (Gilfanov et al. 2003; Olive et al. 2003), and
4. To figure out which characteristics might be caused by having or not having a solid surface, a Comparison of spectral and timing properties is done with those of BH LMXBs. (Wijnands 2001; Barret 2001; Done & Gierli´nski 2003).

However, no consensus has been reached on the right X-ray spectral model for the various subtypes and states of accreting NSs (Barret et al. 2001). The different models give different interpretations of the structures and energy of NS accretion.

 The most detailed theory of accretion disc was proposed by Shakura and Sunyaev in the year 1973, in which the compact object is considered to be a Blackhole. (Shakura et al.1973). Till 1996 no model was there that could explain the formation of the accretion disc around the pulsar. (Lasota et al. 1996) Theoretical models were conceived and tested to enhance knowledge about the highly-dense NS. The models proposed has focus on the radiation process, Radiation regime, phenomena involved, frequency released form of light curve etc. Thus an analysis of X-ray spectra fitting an appropriate model may lead to extract information about the physical and chemical composition and status of the source and its surroundings along with the content of line of sight (LOS).

The Spectrum of energy released by an SXT can be roughly categorised into two parts:

Spectrum during outburst (Periods of high luminosity) and radiation released during the period of quiescence (Periods of low luminosity).

* 1. **Models for the outburst emission:**

 Until 1996, there was a lack of consensus as to the underlying cause of SXT episodes. It is because of instability in the disc or is it because the companion is transferring more mass or a combination of both? (Lasota 1996). One group of models relies on accretion disk instabilities (Cannizzo 1993 and references therein; Huang & Wheeler 1989; Mineshige & Wheeler 1989; Cannizzo, Chen & Livio 1995) and the other on instabilities in the mass transfer from the companion star (Osaki 1985; Hameury, King & Lasota 1986).

 According to Cannizzo (1993) the accretion disk can become locally thermally and viscously unstable due to strong opacity variations caused by the partial ionisation of hydrogen (Cannizzo 1993) which is the basis of the disk instability model (DIM). The mechanism of mass transfer instability (MTIM) on the other hand is based on the gradual expansion of the super adiabatic convective layers of the companion star that is irradiated by hard (E > 10 keV) X–rays, which are supposed to be produced by low-level accretion onto the surface of the compact star (NS) (Hameury, King & Lasota 1986). After the commencement of accretion at a high rate, the high energy radiation is blocked by the growing accretion disk and the companion contracts again within a few weeks, leaving a disk fed at a low rate.

 In a critical review, Lasota (1996) came out with the major shortcoming of these two classes of models: First, the DIMs cannot reproduce the observed recurrence times whereas the MTIM requires a quiescent hard X-ray luminosity at a level of 1034 −1035 erg s−1 and a subgiant or stripped giant companion to produce outburst recurrences in the observed range.

 Contemporary to that King and Ritter-1998 (KR) have demonstrated that the timing analysis of SXTs can be described by a modified disk instability model considering irradiation by the central X-ray source during the outburst. Even a very low level of irradiation has a significant effect on the duration, shape and recurrence time of the outburst (G. Dubus et al., 2001). According to KR, irradiation hinders the disc from returning to the cool state until the central accretion rate is sharply reduced. There could be two possibilities-

(i) If irradiation is capable of ionizing the disc all the way to the edge, the X-ray light curve will be roughly exponential, and the time to recur to the next explosion will be very long as the disc has to be regenerated by mass transfer from its companion star.

(ii) Instead if the X-rays are too weak to ionize the whole disc, the light curve should have an approximately linear decline, returning to quiescence after a timescale. In a linear decay, the outer disc remains cool and is unaffected by the outburst. Since it is likely to contain a significant portion of the disc's mass, viscous evolution can restore the critical density somewhere within the disc relatively quickly, allowing for another explosion. Thus after a series of such linear outbursts, the disc may well enter a much longer quiescent state in which the disc is rebuilt.

KR gives expressions for the critical central accretion rates (Lcrit ) essential to ionize the disc up to to a given radius Rh depending on whether the central source is point-like or disc-like.

Lcrit (point-like) = 3.7 × 1036 R2 ergs s−1 (1)

Lcrit (disc-like) = 1.7 × 1037 R2 ergs s−1 (2) Here Ris the ionized disc radius Rh in units of 1011 cm.

 The same has been shown by T. Shahbaz, P.A. Charles and A.R. King in the year 1998 in the case of sources Aql X–1 (=4U1908+005), Cen X–4 (=4U1456–32), 4U1543–47 and GROJ1744-28 etc.



**Fig. 3: X-ray light curves of SXTs. Top left: 1971 (Vela 5) X-ray outburst of 4U1543–47; top right: 1969 (Ariel 5/ASM) and 1979 (Vela 5) X-ray outbursts of Cen X–4; bottom left: 1974 (Ariel 5/ASM) X-ray outburst of 4U1524–62; bottom right: 1997 *RXTE* X-ray outburst of GS1354–64. E and L denote exponential and linear fits respectively. The data were taken from CSL (This figure is taken from the paper published in MNRAS by T. Sahbaz et al., 1998)**

 To elucidate the temporal behaviour of X-ray binary discs, the current model of disc instability is that of Lasota et al. (2001), F Cotti Zelati (2018), and others. This model proposes that the disc oscillates in a state of cold neutrality (quiescence), and a state of hot ionisation (outburst). During quiescence, matter accumulates in the disc, and during an outburst, it is transported to the compact object.

* 1. **Models for the quiescent emission:**

Quiescent emission is the state in which a source remains for months to years (Bhattacharya, 2010). During this state, X-ray emission is devoid of maas accretion and primarily believed to be from a neutron star's atmosphere. During the quiescent state, the emitted X-ray component may have both thermal and non-thermal components (Rutledge et al, 2002). During quiescent emission, episodic higher accretion is also inferred (Kuulkers et al., 2009), these factors make it challenging to design a model which may fit the emission from an NSSXT in the quiescent state.

S. Campana in the year 1998 proposed that the emission from an SXT during its quiescent state could result from:

 (a) Accretion on the surface of the neutron star;

 (b) Accretion down to the radius of the magnetosphere (when the “centrifugal barrier” is closed);

 (c) Non-thermal processes powered by the rotational energy loss of a rapidly spinning neutron star (Tavani & Arons, 1997);

 (d) Thermal emission from the cooling neutron star (S. Campana, 1998).

 Years later different models based on accretion of matter came up. Menou et al. (1999); and Menou & McClintock (2001) put forward that accretion of matter onto the Neutron Star may be in several flavours such as advection-dominated accretion flow (ADAF), convection-dominated accretion flow and with outflows etc. While Fender et al., (2003) proposed a model based on the accretion of matter onto Jets. Similarly, it was also proposed accretion of matter on (i) to neutron star cooling after long-term (104 yr) heating during outbursts (Brown et al. 1998) and (ii) to emission regimes connected to the existence of a magnetic field (Campana et al. 1998b, Campana & Stella 2000). The neutron star cooling after deep crustal heating proposed by Brown et al., (1998) is the most popular model in explaining the soft component released during the quiescent state of SXTs.

The X-ray spectra thus obtained are usually divided into two spectral components:

1) A soft component modelled as a black body or, more physically, by cooling emission from the entire surface of the neutron star;

2) A hard component modelled as power-law energy tail. The ADAF model is most suitable for hard components.

The bulk of the flux (50−100%) comprises soft components. The power-law tail is present only in a fraction of sources and contributes up to 50% in the (0.5–10) keV energy band (S. Campana, 2001).

Observationally, quiescent X-ray spectra typically include a soft thermal component of less than 2 keV and a hard component of more than 2 keV in Low mass X-ray transients (LMXs) that host an NS. (Campana et al., 1998; Rutledge et al., 1999; Campana, 2004). In soft state, spectra are typically described by a soft and hard component, or by a thermal and a Comptonized component. Depending on the selection of the thermal and Comptonized components there are two classic models: the Eastern model (see Mitsuda et al., 1989) and the Western model (see White et al., 1988). In the hard state, a hard or a Comptonized component dominates the spectra, but a soft or a thermal component is usually still required ( Christian & Swank, 1997; Barret et al., 2000; Church & Baluci´nska-Church 2001; Gierli’nski & Done 2002b). The latest developments distinguish that hard-state atoll sources are associated with steady jets ( Fender, 2006).

The soft part is described in detail by pure hydrogen atmospheric models, and it's usually seen as thermal emissions from the surface of the NS in the cooling stage after an explosion. According to Brown, Bildsten, Rutledge, and Colpi's deep crust heating model (Colpi et al., 2001), the matter that accumulates after the explosion pushes the innermost parts of the crust down, which triggers nuclear reactions and heats up the core. Then, the heat is radiated out in the next phase, which is called quiescence. ( Zampieri, 1995).

The hard component has a good representation in the form of a power law tail. However, the physical nature of this component is still under discussion. Accretion onto the magnetospheric boundary seems to be an intriguing possibility. Although the physics of disc magnetosphere interactions at low rates of accretion (e.g. in a propeller regime) is not fully understood, it is widely accepted that the disk is truncated close to the compact object where the magnetic fields are stronger (F.Coti Zelati, 2018).

The light curves of SXTs are much more complex than the expected simple exponential or slow decay. This suggests that there is still more missing physics to consider. In light of the above facts, it becomes an uphill task to propose a robust model for X-rays that are emitted during the quiescence phase and a single model may not be suitable for every situation.

# CONCLUSION

 Soft X-ray transients are a special class of Low Mass X-ray Binary which radiates X-ray of varying luminosity ranging from 1036 -1038 erg s-1 (during Outburst) (F.Coti Zelati et al., 2018) to 1032 – 1033 erg s-1 (during quiescence) (S. Campana et al.,1998) with soft thermal component below 2 keV and hard component above 2 keV.

 This class of LMXB may contain NS or BH as Compact objects. In this review, we restricted ourselves to NSSXTs only. With the constant development and Commissioning of powerful telescopes, Spectrometer etc. in space observatories like Integral, Chandra, XMM-Newton, Swift, etc. we could defy the hindrance caused by Earth’s atmosphere and become possible to study various types of X-ray binaries. This also made it possible to evaluate the Physical and Chemical structure of NS and the ideal tool for evaluating metal abundances in ISM via absorption spectra. So far around 30 NS SXTs have been identified and listed (Table 1) since the first popular catalogue of LMXB was published by P.R. Amnuel et al. in the year 1978. The most latest catalogue published in the year 2020 comprises 166 LMXBs, out of which 103 are transient.

 The HRXS paved the path of understanding the accretion mechanisms, and various phenomena exhibited by LMXBs e.g. Bursting, Dipping, Eclipsing, QPO, Transient, etc. In turn, it helps us to constrain the content of NS and ISM. The development of a model and our understanding of the nature of the X-ray sources, the phenomenon involved, Chemical and Physical composition of the source go hand in hand. The availability of X-ray data because of the variety of highly sophisticated instruments onboard the X-ray observatories further facilitates exploration. It started with the disk instability model proposed by N.I. Shakura & R.A. Sunyaev in the year 1973, which was later modified by Ghosh and Lamb as the Magnetically Threaded Disk Model in the Year 1979 but till 2001 Spectral modelling of Neutron Stars has been controversial Barret et al., (2001). The spectral analysis of the radiation emitted can be broadly divided into two parts Spectrum during Outburst and Spectrum during the quiescence period. Thermal-Viscous disk instability model explains the transition between Outburst and Quiescence (J.P.Lasota 2001). The spectrum emitted during quiescent is further divided into Soft and Hard State, The two Classical models that were proposed to explain the soft state are models proposed by Mitsuda et al. in the year 1989 namely the Eastern model and by White et al., 1988 namely the Western model. Later, the soft component is well described by pure hydrogen atmosphere models (Zavlin, Pavlov & Shibanov 1996; Heinke et al. 2006) and the deep crustal heating model (Brown, Bildsten & Rutledge 1998; Colpi et al. 2001), the hard component is well represented by a power-law tail model.

 Still, ample scope is there and constant work is going on to address issues like the detection of new SXTs, finalizing the structure of accretion disk, evaluating the origin of X-rays from various regimes, the composition of NS, or evaluating the composition of ISM.

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