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The Fe Kα Emission Line of Intermediate Polar V1223 Sagittarii

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Abstract: We present measurements of the Fe Kα emission line of the intermediate polar V1223 Sagittarii observed with the Suzaku satellite. The spectrum is modeled with an absorbed thermal bremsstrahlung spectrum and three Gaussians for the three components of the Fe Kα lines. We resolve the neutral or low-ionized (6.41keV), He-like (6.70keV), and H-like (7.00keV) iron lines. We also obtain a thermal continuum temperature of 25 keV, which supports a thermal origin of the hard X-rays observed from the shock heated layers of gas between the white dwarf and the shock front. Hence, we believe that the He-like and H-like lines are from the collisional plasma. On the origin of the Fe Kα fluorescence line, we find that it could be partly from reflections of hard X-rays from the white dwarf surface and the $N_{\rm H}$ absorption columns. We also discuss the Fe Kα emission line as veritable tool for the probe of some astrophysical sites.

Key words: binaries — stars: cataclysmic variables — stars: emission lines — X-rays: binaries — X-rays

1. Introduction

Magnetic cataclysmic variables (mCVs) are semi-detached interacting binary star systems in which the primary star, white dwarf (WD), accretes matter from its secondary companion, a low-mass main-sequence star (Tovmassian et al. 2001; Warner 2003; Galis et al. 2008; Aungwerojwit 2011). Matter flowing from the main-sequence star which has filled its Roche lobe, is magnetically funneled onto the magnetic poles of the white dwarf (WD), resulting in accretion of matter at the poles. Close to the white dwarf surface, the infalling matter experiences a shock and is therefore shock-heated to high temperatures (T$\sim 10-50$ keV) at the shock front, releasing hard X-rays in the process through thermal bremsstrahlung cooling (Aizu 1973; Galis et al. 2008). There are two types of mCVs, the polars (AM Herculis type) which are characterized by strong magnetic fields and intermediate polars (IP, DQ Herculis systems) with weaker magnetic fields. Accreted material from the donor reaches the accretor through an accretion disk, accretion stream or disk over-flow accretion (Taylor et al. 1997). The pulse period of the emitted X-rays is the same as the spin period of the white dwarf owing to the misalignment of the WD spin and the magnetic field axis (Norton et al. 1999). The formation of an accretion disk is necessitated by the loss of angular momentum of the infalling gas from the Roche surface of the secondary star (the inner Lagrangian point). The morphology of the accretion disk is determined by the magnetic field strength of the WD (Mukai et al. 2003).

Intermediate polars show disk accretion (accretion onto a magnetic pole from the accretion disk). The moderate magnetic field (B $\sim$ 10 MG) of the WD truncates the inner parts of the disk, allowing the accretion flow to stream down towards the magnetic poles and onto the WD's surface (Galis et al. 2008; Barlow et al. 2006). The rotation period of the WD is asynchronous with the orbital period of the system, i.e., $P_{orb} \neq P_{rot}$ (Chanmugam & Frank 1987). IPs are known to emit harder X–ray spectra, compared to the polars, which is attributed to their high accretion rates (Aungwerojwit 2011).

V1223 Sgr is a magnetic cataclysmic variable of the IP type. The system manifest strong mass accretion-related activity from radio up to gamma-ray regime, on time-scales of seconds to millions of years (Galis et al. 2008; Warner 2003). It is the brightest IP so far observed. The system is a bright X-ray source (4U 1849 -31) (Steiner et al. 1981), located at a distance of about 510 pc. The position of V1223 Sgr in the equatorial coordinate system is: RA 18h 55m 02.31s; DEC -31h 09 m 49.5s. Based on the Beuermann et al. (2004), model A, the value of the B-field of the WD lies in the range (0.5–8)$\times 10^6$ G. The proposed radius and mass of the WD are respectively 4.17×10^8 cm and $1.17 M_\odot$ (Beuermann et al. 2004). Hayashi et al. (2011) also proposed a radius of 6.9×10^8 cm and a mass of $0.82 M_\odot$. The accretion rate is about $\approx 10^{17} gs^{-1}$. This value was obtained from the observed X-ray luminosity, $L_X = 2 \times 10^{34} ergs^{-1}$ (Barlow et al. 2006; Revnivtsev et al. 2008). The WD orbital period, P_{orb}, is 3.37 hr. (Osborne et al. 1985; Jablonski & Steiner 1987), while its spin or rotational period P_{rot} = 746 s (Osborne et al. 1985). The system is known to have prominent long term brightness variations, i.e., outbursts with duration of about 6 hr and amplitude $\geq$ 1 mag (van Amerongen & van Paradijs 1989) and episodes of deep low states (brightness decrease by several magnitudes) (Garnavich & Szkody 1988).

Intermediate polars have been observed to emit Fe Kα lines, which are resolved into fluorescence (6.4

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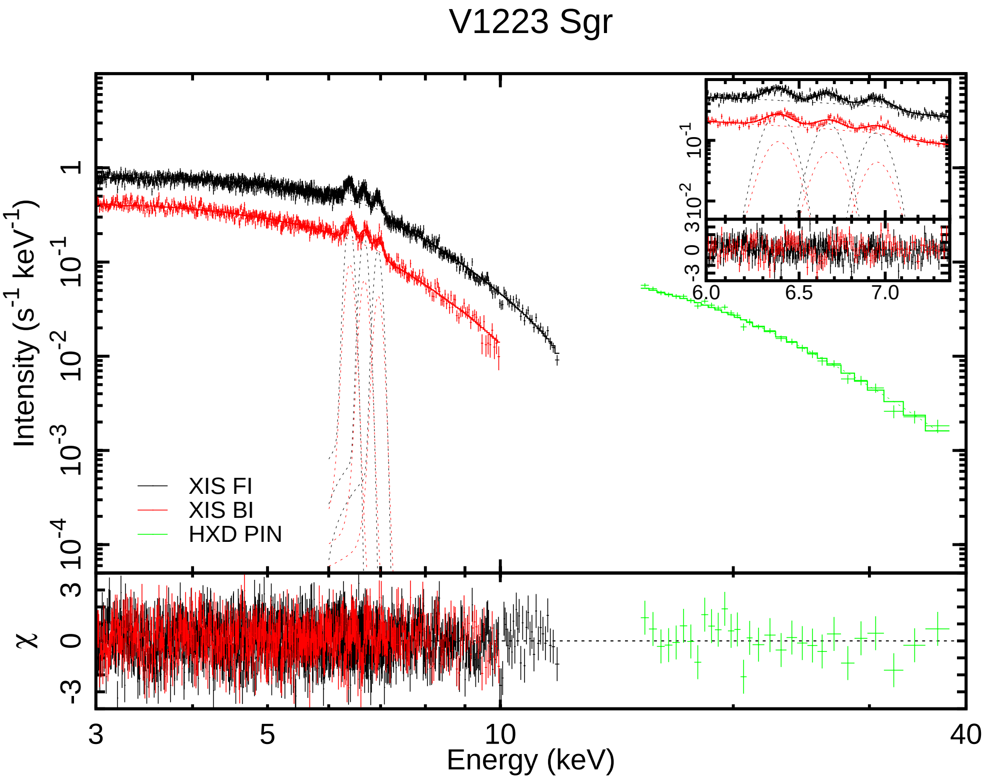

Figure 1. The spectrum of V1223 Sgr. In the upper panel, the data and best-fit model are shown by crosses and solid lines, respectively. Each spectral component is represented by dotted lines. In the lower panel, the residuals of the fit is shown by crosses. The inset in the upper panel is an enlarged view for the Fe Kα complex lines.

keV) and He-like (6.7 keV) and H-like (7.0 keV) lines (Ezuka & Ishida 1999; Mukai et al. 2003; Hellier & Mukai 2004; Yuasa et al. 2010). Reflection of hard X-rays from the white dwarf surface could contribute significantly to the observed Fe Kα fluorescence line in intermediate polars Ezuka & Ishida (1999). Hayashi et al. (2011) discussed the creation of 6.4 keV line emission from V1223 Sgr. as a result of reflection of X-rays from the white dwarf surface of the system. However, the origin of this line in mCVs is yet to be completely addressed. The 6.4 keV iron emission line is typically created by irradiation of the neutral (or low ionized) material (iron) by a hard X-ray source. Eze (2014) discussed in details previous observations of the Fe Kα fluorescence line in Seyfert galaxies, quasars and galaxies. He also showed that the emission of the Fe Kα fluorescence line in the hard X-ray emitting symbiotic star, SS73 17 is from a combination of the reflection of hard X-rays from the accretion disk and the absorption column. The emission of the He-like and H-like line is due to photoionization (and excitation) and collisional ionization/excitation in a hot plasma.

In this paper we discuss the creation of the Fe Kα emission line complex in V1223 Sgr. In Section 2 we present the Suzaku observation of the system, Section 3 contains our data analysis and results and in Section 4 we include our discussions and conclusion.

2. Observation

Observation of V1223 Sgr was done using the Suzaku satellite on 13-04-2007 for 46.2 kiloseconds with ObsID 402002010. Suzaku is Japan's fifth X-ray Astronomy mission. Suzaku was launched on July 10, 2005, to replace the ASTRO-E which failed to reach its orbit during its launch on February 10, 2000. It was developed by the Japanese Institute of Space and Aeronautical Science (ISAS), a branch of the Japan Aerospace Agency (JAXA), in association with NASA. The details of its three instruments can be obtained from Hayashi et al. (2011) and references therein. The satellite's primary mission is to obtain high spectral resolution data of astrophysical objects in the energy range of 0.2–700 keV (soft X-rays to γ-rays), for guest investigator(s) through the sponsorship of a NASA Guest Observer Program. After one year from the end of the period of observation, the collected data are placed in the Suzaku Public Archive for public usage. The V1223 Sgr data (ObsID: 402002010) used in this paper was retrieved from the Suzaku Public Archive.

3. Data Analysis and Results

Our data was analyzed using the version 2.0 of the offline standard Suzaku pipeline products and the analysis software: HEASOFT version 6.11 and XSPEC version 12.7 (Dorman & Arnaud 2001). The data were reduced as follows: All data collected when the satellite was in

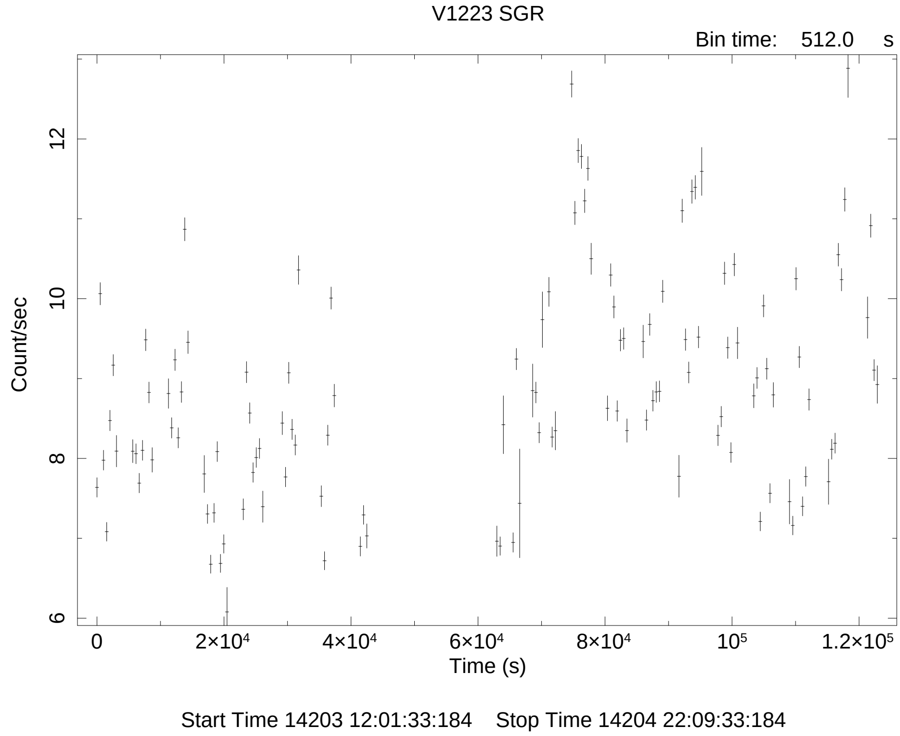

Figure 2. Light curve of V1223 Sgr, showing no sign of stellar flaring activity in the source at the time of observation.

the South Atlantic Anomaly were discarded for both the XIS sensors and the HXD PIN detectors. Also discarded, were the data obtained when the Earth elevation and Earth-day elevation angles were respectively less than 5 and 20 degrees. This was done to reduce the effects of contamination due to the background X-ray noise. Since the image of V1223 Sgr contains no detectable weak point sources, a 250″ radius of extraction was used for the extraction of events for the XIS detectors to produce the source spectrum. The same radius was also used to extract the XIS background spectrum with no apparent sources and was offset from the source and corner calibrations (calibrations at the four corners of the CCD image). This background spectrum consists of the non-X-ray background (NXB) and diffuse X-ray background (DXB). Since our object is off the galactic plane, we assumed that the contribution of the Galactic Ridge X-ray Emission (GRXE) is insignificant; hence it was ignored. The response files: Redistribution Matrix File and Ancillary Response File were generated for the XIS detectors using the FTOOLS, `xisrmfgen` and `xismarfgen` commands respectively. The XIS 0, 2 and 3 are front-illuminated (FI) chips whose features are similar. Consequently, the spectra of XIS 0 and 3 were merged and referred to as FI. XIS 2 had been out of service since November 9, 2006 due to operational fault, consequently no data was obtained from this mirror. XIS1 is a back-illuminated (BI) chip and its spectrum is referred to as BI.

The analysis of the HXD PIN detector was done by downloading the non- X-ray tuned PIN background files and the appropriate response matrix files for the observation, as generated by the Suzaku team. The HXD PIN data analyzed were those with the 12 to 40 keV energy range. The good time intervals (when both data and background models were available) were merged using the `mgtime` FTOOLS to obtain a common value for both the PIN background and source event files. The source and background spectra for the source were extracted using the XSELECT filter time file routine. The dead time of the observed spectra was corrected for, using the `hxddtcor` command of the Suzaku FTOOLS. The observation exposure time for the derived background spectrum was increased by a factor of 10 to accommodate for the event rate in the PIN background event file which was made 10 times higher than the real background for suppression of the Poisson errors, in accordance with the standard Suzaku analysis procedure.

Using XSPEC version 12.7, the spectrum was modeled using the absorbed thermal bremsstrahlung model with a partial-covering matter and a full-covering matter. In order to eliminate contamination of the XIS FI and BI data below the 3 keV energy band, due to the intrinsic absorptions (multi-column absorption and ionized absorption of the pre-shock gas), we discarded the data within this energy range in the fitting. We added three Gaussian lines for the three components of the Fe Kα emission lines. The chi-squared fitting of the spectra covers 3-10 keV energy range for the XIS BI data, about 3-12 keV for the XIS FI data and 15- 40 keV for the HXD PIN data. The energy range above 10 keV was not considered for the XIS BI data, since the instrument background is higher relative to the XIS FI detectors above this energy level. The cross-normalization

Table 1
Best fitting parameters of V1223 Sgr by the thermal Bremsstrahlung Model

Parameter	Value	Unit
$N_{\rm H}^{\rm f}$	2.3 ± 0.2	10^{22} cm^{-2}
$N_{\rm H}^{\rm p}$	72 ± 5	10^{22} cm^{-2}
C	0.41 ± 0.03	
kT	25 ± 3	keV
$F_{\rm cont}$	34.5 ± 0.3	10^{-3} photons s^{-1} cm^{-2}
$E_{6.4}$	6.38 ± 0.01	keV
$F_{6.4}$	15.7 ± 0.7	10^{-5} photons s^{-1} cm^{-2}
$\rm EW_{6.4}$	89^{+17}_{-8}	eV
$E_{6.7}$	6.67 ± 0.01	keV
$F_{6.7}$	11.3 ± 0.6	10^{-5} photons s^{-1} cm^{-2}
$\rm EW_{6.7}$	59^{+18}_{-8}	eV
$E_{7.0}$	6.95 ± 0.01	keV
$F_{7.0}$	8.3 ± 0.5	10^{-5} photons s^{-1} cm^{-2}
$\rm EW_{7.0}$	102^{+58}_{-36}	eV

factor for the PIN and XIS data was fixed at the typical value of 1 for XIS and at 1.16 and 1.18 for HXD PIN, for XIS-norminal attitude and HXD-nominal attitude respectively. The Fe Kα emission lines, low ionized or neutral (6.41 keV), He-like (6.70 keV) and H-like (7.00 keV) iron lines, were resolved clearly as shown in Figure 1.The spectral parameters were presented in Table 1.

In our search for the origin of the Fe Kα fluorescence line in our source, we added an XSPEC reflection model to the absorbed thermal bremsstrahlung model. The spectral parameters are presented in Table 2.

We generated an XIS light curve of the source after background subtraction. Both the BI (XIS 0) and the FI (XIS 1 and 3) data were combined. The energy range used is 0.1-12.0 keV; while the bin size is 512.0 s. The light curve of V1223 Sgr shows no flaring activity at the time of observation as shown in Figure 2. The best fitting parameters of V1223 Sgr for a thermal bremsstrahlung model with a partial-covering matter and full-covering matter are shown in Table 1.

4. DISCUSSIONS AND CONCLUSION

4.1. Hard X-rays from V1223 Sgr

The production of hard X-rays in IPs such as V1223 Sgr is by the magnetically channeled accretion column, whose impact on the WD poles is followed by thermal bremsstrahlung cooling by free electrons with kT of the order of 10 keV and above (Cropper 1990; Warner 2003). The emission is assumed to be through the post-shock region, which is below the shock front created from the impacting accretion column. The observed soft X-rays on the other hand are emitted through the absorption and reprocessing of the hard X-rays in the plasma close to the surface of the WD. The absorbed thermal bremsstrahlung model produced a statistically acceptable spectral fit, which agrees with the results of Galis et al. (2008), in which the broad-band spectra (3-100 keV) of V1223 Sgr were well fitted by a thermal bremsstrahlung model, with a post-shock region temperature, kT of about (20–25 keV). Regarding the harder component, the HXD PIN data were also fitted well by the model, although the data points are fewer compared to that of the XIS FI and BI detectors.. We obtained a strong bremsstrahlung continuum with a temperature of 25 keV, coupled with the strong Fe Kα line consisting of neutral or low-ionized (6.41keV), He-like (6.70keV), and H-like (7.00keV). This signifies that the hard X-rays from V1223 Sgr are thermal in origin.

Table 2
The reduced χ^2 (R χ^2), full χ^2 (F χ^2) and degree of freedom (dof) for the absorbed bremsstrahlung and an absorbed bremsstrahlung plus XSPEC reflect model, F–test probability and reflection normalization

Parameter	Value
BM,(R χ^2)/(F χ^2)/dof	1.15/2256.6/1963
BRM,(R χ^2)/(F χ^2)/dof	1.08/2117.9/1962
FP	8.10×10^{-29}
RN	0.30

Parameters are the absorbed bremsstrahlung model (BM), an absorbed bremsstrahlung plus XSPEC reflect model (BRM), F–test probability of null result for the BRM (FP) and reflection normalization (RN).

4.2. On the Origin of the Fe Kα Emission Line

We searched for reflection of hard X-rays in this system by adding the XSPEC reflection model to the absorbed thermal bremsstrahlung model. As can be observed from Table 2, there is evidence that the Fe Kα fluorescence emission line is created by the reflection of hard X-rays from about 30% of the surface area of the white dwarf. Similar result was obtained by Eze (2014) in the hard X-ray emitting symbiotic star SS73 17. It has been also noted that a significant portion of the hard continuum is believed to result from reflection from the WD surface (Galis et al. 2011; van Teeseling et al. 1996). In addition to the WD surface, the reflection could also come from the cold gas on or near the WD surface or pre-shock region and from the NH absorption column. (see Yuasa et al. 2010; Hayashi et al. 2011; Eze 2014), and the accretion column. Hayashi et al. (2011), suggested that the reflector is the WD, since the solid angle, $\Omega/2\pi = 0.91 \pm 0.26$, which approximates to unity but our present result shows that reflection accounts for about 30% of the emission, meaning that the rest could be from reflection of hard X-rays from the NH absorbing column (see Eze 2014)

4.3. The 6.7 and 7.0 keV Emission Lines

In most hot astrophysical plasmas like hot plasmas in mCVs, hard X-ray emitting symbiotic stars (hSSs) and AGN, photoionization (and excitation) and collisional ionization/excitation are continuous ongoing processes. Hence there is the production of He-like and H-like iron emission lines in such environments (see e.g., Eze 2014). The issue then is, which of these processes dominates in any given source, which is not usually simple to resolve.

In order to resolve this issue, we need to measure the G ratio of the Fe XXV line and compare with the measured bremsstrahlung temperature. Unfortunately, the accuracy of our He-like and H-like EW measurements with the Chandra HETG and Suzaku CCDs are not adequate to constrain measurement of the G ratio of the Fe XXV line sufficiently to merit comparison with the measured bremsstrahlung temperature (see Eze et al. 2010). However, we believe that since the hard X-rays from the source is thermal in origin, it is likely that theses emission lines are produced through collisional plasma rather than photoionization. This could and should be tested with future Astro-H observations.

4.4. Fe Kα Emission Line as Veritable Tool for the Probe of Hot Astrophysical Sites

The emission of the Fe Kα lines is of great importance for the study of hot astrophysical sites. It is one of the main features that characterize the X-ray spectra of a sources like mCVs, hard X-ray emitting symbiotic stars, X-ray binaries and AGN. This is due to the fact that iron is far more abundant than any other heavy metal in these sources. Consequently, the iron fluorescence emission line (6.4 keV) is a hallmark of accretion driven X-ray sources (Piro et al. 1993). The Fe Kα emission line is a veritable tool used for the study of the geometry, physics and kinematics of astrophysical sites. The thermal origin of the X-ray emission of some sources like galaxy clusters was confirmed upon the discovery of the 6.7 keV iron line in their X-ray spectra (see Mitchell et al. 1976).

Analysis of the Fe Kα emission spectrum can be used to deduce basic physical properties within the emitting region, such as temperatures, densities, excitation conditions, ionization balance, elemental abundances and electric- and magnetic-field distributions (Jacobs et al. 2004; Kahn 2002). The parameters that are usually employed in this study are line energy Eα, equivalent width EWα, intensity Fα, and line profile (line width). Here, α stands for the relevant emission line.

The line energy or line centroid shows the state ionization in a medium. The line energy increases slowly from 6.4 keV in Fe I to 6.45 keV in Fe XVII, and then sharply to 6.7 keV and 7.0 keV in Fe XXV and Fe XXVI respectively. Several authors (e.g., Fabian et al. 1989; Stella 1990; Matt et al. 1992, among others) pointed out that the line energy equally depends on Doppler and gravitational shifts, if the accretion disk is that of a black hole or an AGN. It has been suggested that in a highly ionized medium, gravitational red-shift could cause the 6.7 keV energy line to be observed as the 6.4 keV line emissions (Hayakawa 1991). In addition to these effects, Kallman & White (1989), argued that Compton scattering contributes significantly in the line broadening, and this depends on the geometry and optical depth of the medium.

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