BENIN JOURNAL OF PHYSICAL SCIENCES
BJPS Vol. 1(1), June, pg. 222-230 (2024)
www.bjps.org.ng

On the Flickering Behaviour of FO Aqr in the Presence of Thermal Bremsstrahlung

S. ESAENWI*,1, J. O. VWAVWARE2, and F. B. SIGALO1

[1]Department of Physics, Rivers State University, Port Harcourt, Rivers State, Nigeria.
[2]Department of Physics, Dennis Osadebay, University, Asaba, Delta State, Nigeria.

Received: 12/06/2024 ***Accepted:*** 30/06/2024

Abstract

The results of our Japanese HEASARC data reduction from Magnetic Cataclysmic Variable (mCV) FO Aqr is clearly reported in this paper. On June 5, 2009, the Suzaku team used the Suzaku satellite to observe FO Aqr for 33.4 ks with an observation ID of (404032010). Three Gaussian lines were detected via Thermal Bremsstrahlung technique which represented iron lines in our system's spectrum modeling. The equivalent width and neutral or low-ionized continuum flux at the 6.40 keV, He-like (6.71 keV), and H-like (7.01 keV) iron lines were resolved by comparing data analysis of the source using XSPEC versions 14.5 and 12.7. The absorbing hydrogen column density at complete and incomplete covering are clearly identified. The bremsstrahlung cooling caused by hard X-rays produced Fe Kα lines in the target (FO Aqr) at its shock front. We deduced that the source is flickering through the variability in its spectral parameters though the light curve shows no signs of a flare.

Keywords: *Cataclysmic Variables, flickering, flares, continuum flux*

1. INTRODUCTION

FO Aqr is an Intermediate polars (IPs), which are a sub-class class of magnetic cataclysmic variable (CV) that contain a weakly magnetic white dwarf (WD) primary and a low-mass companion located in the constellation Aquarius (Kennedy et al, 2020). In the usual CV system, the mass is transferred from the companion star to the WD, which forms an accretion disk extending down to the WD surface or accretion column on the WD's pole, toward which the accreting matter is channeled by the WDs magnetic field (Takata et al, 2022). Numerous

---

*Corresponding author, e-mail: esaenwi.sudum@ust.edu.ng efforts to identify new CVs and candidates have been made in previous works, and the number of known CVs is rapidly increasing with recent photometric and spectroscopic all-sky surveys (Szkody et al. 2021; Sun et al. 2021). The methods of confirming CVs are mainly divided into three types, namely, the observation of dwarf-nova outbursts, identification of orbital/WD spin variations in photometric light curves, and confirmation of CV-like spectral properties (John, 2020). The Cataclysmic Variable Catalog by John, (2020) offers a vast list of the known CVs and the CV candidates found in previous studies. Aquarius is a constellation that harbors the binary intermediate polar (FO Aqr) under investigation (Pekön, and Balman, 2012). The binary intermediate polar consists of a white dwarf primary star and a secondary companion star, with orbital periods roughly 4.85 hours apart (Osborne and Mukai, 1989). A noteworthy feature of the FO Aqr system is usually a strong physical flicker that reappears every 20.9 minutes and correspond to an accreting white dwarf's rotational period (Patterson and Steiner, 1983). The thermal bremsstrahlung model, which describes the production mechanism of X-rays through hot gas, is the technique used in this work. The stellar gas is actually a hot plasma because of its extremely high temperature and highly ionized state for the majority of the elements. When an ion approaches the negatively charged electrons in this plasma, force is exerted, leading to the emission of electro-magnetic dipole radiation due to an accelerating charge. The electron loses energy during this process and violently slows down demonstrating a process known as thermal bremsstrahlung. As a result, the gas cools and the temperature drops sharply as the electron slows down making the plasma loss energy. This kind of radiation is known as free-free radiation since the electron is not attached to any ions during the interaction. Comprehending the process of mass transfer in the FO Aqr systems is crucial to the understanding of CVs and other similar binary candidates possessing strong magnetic moment which is capable of truncating the accretion disc formation thus causing the stellar primary to spin up faster due to mass transfer. (Wijnands and van der Klis, 1998), (Simone, et al., 2015). The purpose of this work is to perform a spectroscopic analysis of the FO Aqr data, examine the source's light curve to determine whether it exhibits intrinsic variation, determine whether the source is flickering and determine the potential source of the Fe kα lines that are produced due to hard X-ray generated within the source. When rapidly ascending charged particles interact with the plasma medium, flares are generated. This massive acceleration of charged particles are usually assumed to form by the phenomenon of magnetic interconnection. This also explains why the active regions of stars, where magnetic fields are much stronger, are usually where stellar flares also originate (Eze and Esaenwi, 2017). To understand the structure and evolution of the cataclysmic variables especially FO Aqr, we will need accurate values for its mass, dimensions, mass transfer rates, and other physical properties (Qi-Bin, 2023).

2. MATERIALS AND METHOD

Data of FO Aqr were collected from HEASARC which is one of the main sources of information used in this work. The database provided the FO Aqr data, which we downloaded and processed using HEAsoft 8.90, XSPEC 12,7 and XSPEC 14.5. The Suzaku team observed FO Aqr for 33.4 ks on June 5, 2009, using observation identity (obsid: 404032010).

Spectral Analysis for XIS Data

XSELECT file filter technique was carefully adopted to sieve out the background and source files form the spectra for individual observations. This was done to distinguish all source spectra from the source background. As a result, we separated the target and its background for all desired zones with the aid of XSELECT. Generation of all response files (RF), random matrix files (RMF), and ancillary response files (ARF) were carried out using X-ray imaging spectrometer matrix file generator (XISRMFGEN) and X-ray imaging spectrometer matrix random file generator (XISMARFGEN) tool on the XSELECT software respectively. Our data was also subjected to a spectral analysis using XSPEC 12.7 and 14.5 to produce the target spectral parameters needed to study the iron lines. The errors obtained in this study were discovered by the application of the XSPEC error command. Using the Hard X-ray detector dead time corrector (HXDDTCOR) tool on the XPEC software, we were able to recover and merge the spectra from the observation of FO Aqr for both analysis to account for all deadtime. XSELECT software was used to fix the source's off-axis placement after choosing the proper response file. We are particularly interested in the 6.7 keV, and 7.0 keV emissions, hence we adopted the thermal bremsstrahlung model. The He-like 6.7 keV and the H-like 7.0 keV were estimated. The FO Aqr spectra for XSPEC versions 12.7 and 14.5 were merged and plotted as seen in Figure 1. The emission lines at 6.7 and 7.0 keV are visible in the spectrum, which is fitted with a basic thermal bremsstrahlung model. In order to prevent intrinsic absorption within the source, which could have an impact on data analysis at that temperature, energies below 15 keV were disregarded for hard X-rays. We also disregarded energy above 40.0 keV in order to keep the signal-to-noise ratio high. After the light curve was created, we isolated it to investigate whether the source displayed any signs of flares and to determine whether it was flickering.

3. RESULT AND DISCUSSION

To determine the source of the emission lines, we examine all recovered spectra of FO Aqr. Strong Hydrogen-like and Helium-like emission were found in the FO Aqr spectra, as seen in Figure 1, at centroid energies of 6.4, 6.7, and 7.0 keV. There were also identifiable Fe xxvi and Fe xxv lines. In the Suzaku XIS spectra of FO Aqr, the Fe Kα lines of Fe (Hydrogen-like and Helium-like) are clearly visible capable of causing an intrinsic variability and flickering effect. The emission spectrum produced via the Thermal Bremsstrahlung coincides considerably with a photoionized plasma model Sako et al., (2000) and is congruent with result obtained from the freezing flow plasma model (Liedahl, 1999). Figure 2 shows the light curve of FO Aqr indicating no evidence of flare in the source for both analyses. Additionally, we assumed that all lines in the spectrum remain saturated at all column densities in order to fit the data. Based on these conjectures, we estimated the hard X-rays of FO Aqr to emanate from surrounding of the accretion plasma which irradiate the accretion disk, causing Fe Kα lines to appear in the model (Thermal Bremsstrahlung) used. Here, we found that bremsstrahlung freezing due to free electrons produced an average temperature of nearly 27.01 keV causing hard X-rays in FO Aqr.

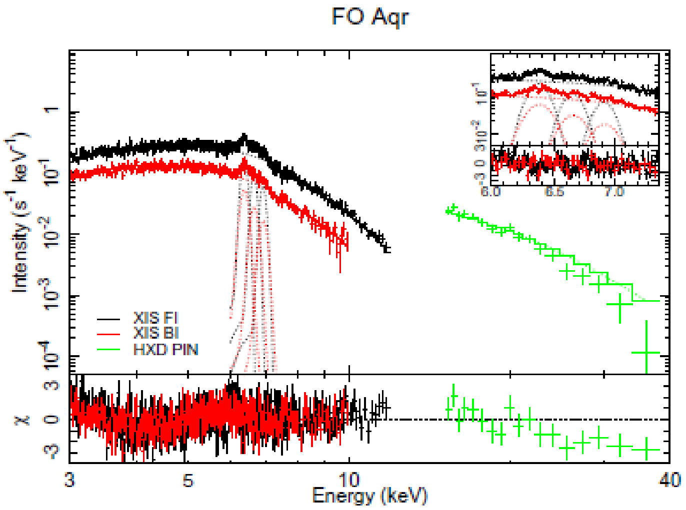

Figure 1: *FO Aqr spectra with a pointed X-ray spectral observation of Fe Kα, using thermal bremsstrahlung model. An enlarged image of the resolved iron line complex is displayed in the insert.*

In order to analyze the light curve, we plotted luminosity (count/sec) against time for a merged result of both XSPEC versions 12.7 and 14.5 and made the assumption that while the emission is scattered along our view, the observed reprocessed emissions produced in the collisionally-ionized media are entirely un-scattered (Nwachukwu et al., 2015). Nonetheless, because of collisional ionization, we saw a high absorption of the hard X-ray partial covering and a low scattering of the hard X-ray full cover in the source. This is in line with Table 1 depiction of a low accretion column covering the hot interaction zone. Table 2 shows a complete absence of accretion column indicating a clear evidence of variability in the source meaning that the source is flickering. The light curve lacks all indication of intrinsic fluctuation or the presence of flares in the system but also support a flickering process. We discover that the data fits quite well into a straightforward model of thermal bremsstrahlung spectra.

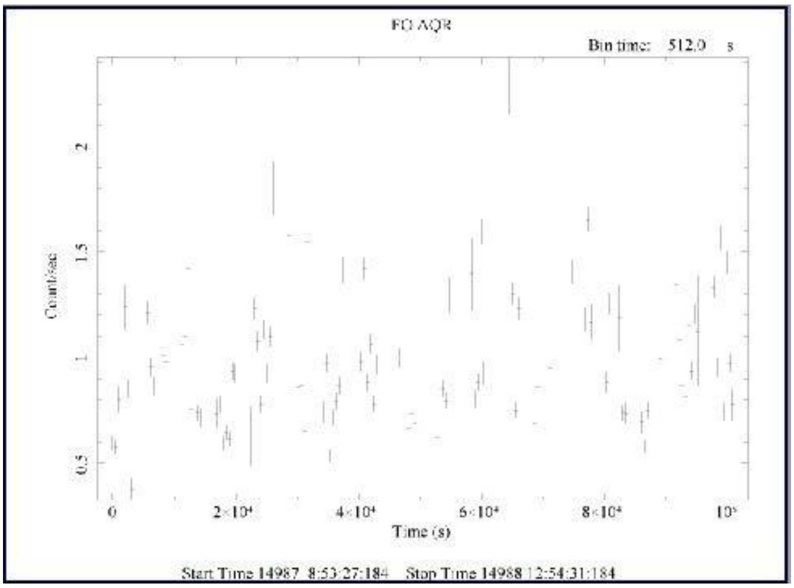

Figure 2: *The FO Aqr light curve indicates that the source is neither flickering or flaring.*

The source's data parameter is used to determine the mean value of the Fe Kα emission estimation, which are summarized in Table 1 and Table 2 for XSPEC version 14.5 and XSPEC version 12.7 respectively. It is recommended that sample attributes that are obtained from our findings consider potential biases that could lead to variability in the two method of analysis used. Not every stellar target can be treated with thermal bremsstrahlung model, hence we suggest that models that suit specific sources should be adopted accordingly.

Table 1: *FO Aqr observable parameters and errors*

Parameter	FO Aqr (Value ± Error) for XSPEC 14.5	Units
(KT)	27.00 ± 2.00	KeV
(Fcounts)	37.00 ± 1.00	photons $s^{-1}cm^{-2}$
E6.41	6.37 ± 0.01	(KeV)
E6.7	6.65 ± 0.01	(KeV)
E7.01	**6.92 ± 0.02**	**(KeV)**
F6.41	**28.40 ± 1.00**	**10^{-5} photon s^{-1} cm^{-1}**
F6.71	**16.60 ± 1.00**	**10^{-5} photon s^{-1} cm^{-1}**
F7.01	11.10 ± 1.00	10^{-5} photon s^{-1} cm^{-1}
EW6.41	149.00 +39, -30	eV
EW6.71	80.00 +33, -54	eV
EW7.01	49.00 .00 +26, -22	eV
N_H^f	10.20 ± 0.20	-
N_H^p	143 +56, -25	-
C	0.61 ± 0.07	-

Table 2: *FO Aqr observable parameters and errors*

Parameter	FO Aqr (Value ± Error) for XSPEC 12.7	Units
(KT)	27.00 ± 2.00	KeV
(Fcounts)	20.80 ± 1.00	photons $s^{-1}cm^{-2}$
E6.41	6.41 41± 0.01	(KeV)
E6.7	6.66 ± 0.02	(KeV)
E7.01	**6.95 ± 0.025**	**(KeV)**
F6.41	**3.30 ± 0.20**	**10^{-5} photon s^{-1} cm^{-1}**
F6.71	**2.90 ± 0.30**	**10^{-5} photon s^{-1} cm^{-1}**
F7.01	1.10 ± 0.30	10^{-5} photon s^{-1} cm^{-1}
EW6.41	28 ± 0.30	eV
EW6.71	32.00 ± 1.00	eV
EW7.01	109 ± 4.00	eV

Line Centroid Energy: We determined the centroid energy of FO Aqr from this investigation, as can be seen in the spectrum (Figure 1). Three distinct weighted mean line centroid energies are compiled in Tables 1-2 for both XSPEC versions. Every pair of measures came from our examination of the data. The intrinsic line width was constant in our spectral-fitting results, from which each mean centroid energy was generated as displayed in Tables 1-2. The three mean centroid energies are computed within the range of 6.4 KeV, 6.7 KeV, and 7.0 keV. It should be noted that although the mean centroid energies have uncertainties of 0.01 and 0.02 keV for both XSPEC version indicating that the brightest sources may have influenced them.

Equivalent Width of Emission: The spectra-parameters for the Fe Kα emission width for FO Aqr are presented in Tables 1-2 as a result of the both analyses carried out. We estimated three weighted mean EW values for each analysis and estimated the values by presenting the emission width in all spectral plots. Tables 1-2 summarizes the mean EW values that were obtained. The EW's values, which range from 149eV to 49eV with an error of 39eV or less for XSPEC 14.5 and 109eV to 28eV with error of 4eV or less, depend on how it is estimated and the sensitivity of the software version. Element abundances determine the Fe Kα emission equivalent width (EW), and the time interval between changes in the flux level and the Fe Kα emission flux influences the EW estimation made during the observation. Due to instrumental error in data analysis, the deviation of the EW distribution measured from the Suzaku data should not be more than ≈ 180 eV (Ikeda et al., 2009).

Fluxes: The fluxes displayed in Tables 1-2 are emissions seen in FO Aqr hard X-ray spectrum which represent the amount of energy emitted by the source during a specific period of time and space. The weighted mean fluxes, F6.4, F6.7, and F7.0, were estimated at (28.40 ± 1.00, 16.60 ± 1.00, and 11.10 ± 1.00)10^{-5} photon s^{-1} cm^{-1}, consistent for XSPEC 14.5 and (23.30 ± 0.30, 12.90 ± 0.30, and 10.10 ± 0.30)10^{-5} photon s^{-1} cm^{-1}, consistent for XSPEC 12.7. The Tables 1-2 provides a summary of the mean line flow values that were obtained for both XSPEC analysis. The physical interpretation of this result is that it takes less energy to ionize hydrogen than helium and more energy to ionize the iron core of the source indicating a complete lack of flare in the source. The average line's values range from 28.40×10^{-5} photon s^{-1} cm^{-1}, 16.60×10^{-5} photon s^{-1} cm^{-1}, and 11.10×10^{-5} photon s^{-1} cm^{-1} with an error of 0.01 photon s^{-1} cm^{-1}. The line's values are sensitive to how they are estimated. Nonetheless, based on our examination of the data sample, we can claim that the results are compatible with earlier research on the Fe Kα line, Eze and Esaenwi, (2017) albeit with some error variance. To lower the mistakes, more accurate analysis tools and more sensitive apparatus are needed.

4. CONCLUSION

To determine whether the source is flickering, we have examined the light curve and spectra of FO Aqr using and old and recent version of XSPEC software. Initially, we examined the light curve to see if the source showed signs of flare and intrinsic variation using XSPEC version 14.5. However, we used XSPEC version 12.7 to do spectral analysis on the same data to examine its spectral variability. Tables 1-2 shows clear evidence of variability in the stellar parameters indicating that there is changes within the source with time using these dual advance software probe. On the estimation of fluxes, we modelled the spectrum with Gaussian traces for the three Fe Kα emission, using the thermal bremsstrahlung model. Complete-covering and Incomplete-covering matter absorption were totally absent in the XSPEC version 12.7 but clearly shown in XSPEC version 14.5 indicating clear evidence of variability, hence we recommend the use of XSPEC version 14.5 for subsequent analysis due to its advanced features. The neutral or low-ionized iron line complex (6.4 keV), Helium-like Fe K line complex (6.7 keV), and Hydrogen-like iron line complex (7.0 keV) were satisfactorily resolved from the spectra and light curve studies. According to our bremsstrahlung model, the iron line complexes in FO Aqr at 6.4 keV are partially attributed to reflection on the white dwarf interface and the inner accretion friction, as well as collisional excitation of FO Aqr system. The harsh X-ray radiation between the hot white dwarf and the accretion disk at the post-shock region is what caused the 6.7 and 7.0 keV lines to form. The light curve makes it evident that we did not see any flare in the source. The thermal bremsstrahlung continuum, whose average temperature in the source is 27 keV, is the source of the hard X-rays.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Eze, A.C., Eze, R.N.C., and Esaenwi, S., (2017) On the contribution of the 6.7 keV line emission of the Algol binary system to the 6.7 keV from the galactic ridge. *Turkish Journal of Physics*, 41, 277-284. Doi: 10.3906/fiz-1703-1.

[2] Ikeda, S., Awaki, H., and Terashima, Y., (2009), X-ray emission on variable stars. *Astrophysical Journal,* 56, 692-100

[3] John, R. T. (2020). Follow-up Studies of Five Cataclysmic Variable Candidates Discovered by LAMOST, *The Astronomical Journal,* 160, 151-152

[4] Kennedy, M. R., Garnavich, P. M., Littlefield, C., Marsh, T. R., Callanan, P., Breton, R. P, Augusteijn, T., Wagner, R. M., Ashley, R. P., and Neric, M. (2020). Optical spectra of FO Aquarii during low and high accretion rates, *Monthly Notices of the Royal Astronomical Society*, 495, 445-462.

[5] Liedahl, D.A. Van Paradijs, J.A., and Bleeker, M. (1999). On the X-Ray Spectroscopy in Astrophysics, eds. *(Berlin: Springer),* 34, 245-246

[6] Nwachukwu, E. R., Eze, A., Nwafor, J., Esaenwi, S., Okeke, P., Ebisawa, K., and Smith, R., (2015). Contribution of the 6.7 keV Emission line from Stellar Flares to the Galactic Ridge X-ray Emission. *International astronomical union General Assembly*, 22, 299-303.

[7] Osborne, J. and Mukai, K. (1989). New Orbital and Spin Ephemerides of the Intermediate Polar Fo-Aquarii H:2215-086. *Monthly Notices of the Royal Astronomical Society*, 238, 1233-1246.

[8] Patterson, J. and Steiner, J. E. (1983). H2215-086 -King of the DQ Herculis stars. *The Astrophysical Journal.* 264; 346-366.

[9] Pekön, Y. and Balman, Ş. (2012). Orbital-phase-resolved Spectroscopy of the Intermediate Polar FO Aqr Using XMM-Newton Observatory Data. *The Astronomical Journal*. 144; 53-54.

[10] Qi-Bin Sun, Sheng-Bang Qian, Li-Ying Zhu, Wen-Ping Liao, Er-Gang Zhao, Fu-Xing Li, Xiang-Dong Shi, and Min-Yu Li, (2023). Nine New Cataclysmic Variable Stars with Negative Superhumps. *Astrophysical journal*, 33, 205-209

[11] Sako, M., Kahn, S.M., Paerels, F.B.S., and Liedahl, D.A. (2000). *Astrophysical Journal*, 543, 115-120

[12] Simone, S., Thomas, J. M., Elmar, K., Christian, K., Simon, V., Thomas, R. M., Ester A., Vikram, S., and Susana, C. C. B. (2015). Accretion-induced variability links young stellar objects, white dwarfs, and black holes, *Science Advances*, 19, 984-988

[13] Sun, Y., Cheng, Z., Ye, S., Osaki, J. Y., and Yu, Y. A. (2021). System parameters of three short-period cataclysmic variable stars, *Astrophysical Journal*, 257, 65-68

[14] Szkody, P., Olde Loohuis, C., and Koplitz, B., (2021). System parameters of three short period cataclysmic variable stars, *Astrophysical Journal*, 162, 94-98

[15] Takata, X. F. Wang, A. K. H. Kong, J. Mao, X. Hou, C.-P. Hu, L. C.-C. Lin, K. L. Li, and C. Y. Hui, (2022). Searching for Cataclysmic Variable Stars in Unidentified X-Ray Sources, *The Astrophysical Journal*, 936, 134-135

[16] Wijnands, R., and van der Klis, M., (1998). Origin of iron lines from the surface of cataclysmic stars, *Nature Astrophysiscs*, 394, 344-345