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On the contribution of the 6.7 keV line emission of the Algol binary system to the 6.7 keV line emission from the galactic ridge

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Abstract: We carried out spectroscopic analysis of the extracted stellar flare of the Algol binary system observed using the Suzaku satellite (OBSID: 401093010), and resolved a strong 6.7 keV line emission. The 6.7 keV line emission of the Algol binary system is similar to the 6.7 keV line of the galactic ridge X-ray emission (GRXE). The equivalent width (EW) compared favorably with the EW of the 6.7 keV emission line obtained from different galactic ridge regions. In the galaxy, we have a reasonable number of Algol binary systems and many other stars as strong coronal X-ray emitters characterized by frequent quiescent and super flaring phases as observed by Suzaku, and these systems could contribute to the 6.7 keV emission line from the galactic ridge.

Key words: Binaries, Algol-stellar flares, X-ray, galactic ridge X-ray emission

1. Introduction

Flare stars are variable stars that exhibit violent and sporadic flare activity. Satellite observations across the radio, optical, and X-ray band regions have revealed the presence of dense chromospheres and coronae in flare stars. The dynamo motion during the rapid rotation of flare stars generates a magnetic field that is dissipated in the coronae [1]. The eruption in the magnetic field generates stellar flares. The stellar flares last for a few minutes and this occurs as a result of the intense dramatic increase in the brightness during the rapid rotation of these stars. The magnitude of coronal activities in flare stars is about 3 times more energetic than that in the sun [2]. Spots are also known to exist on the surface of flare stars; therefore, the physical processes involved in the atmosphere of flare stars are probably not distinct from those occurring in the sun. There are numerous X-ray flare stars including T. Tau stars, RS CVn (RS Canum Venaticorum variables) systems, Algols, W Uma, and NU UMa systems [1–4] that have been observed in the Milky Way.

Algol (Beta Persei) is an X-ray binary system in the constellation Perseus. It is located about 92.8 light years from the sun with short orbital period of $\sim$ 2.9 days. Algol was first detected in X-ray energy region by Small Astronomy Satellite (SAS) 3 in October 1975 [5]. The Sounding rocket flight confirmed that Algol's stellar flares are strong X-ray emitters. The mass-transfer model, Roche lobe overflow, or stellar wind mechanisms explains the X-ray emission from the Algol binary system [6]. The presence of elemental abundance (S, Si, Al,

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Mg, Ne, Fe, C, N, O) in the convection zone (chromospheres/coronal) during the quiescent and peak flared phases of the Algol binary system have been observed and confirmed by the GINGA (Japanese for 'galaxy' X-ray), ASCA (Advanced Satellite for Cosmology and Astrophysics), and XMM-*Newton* (X-ray Multi-Mirror Mission) satellites [7–9]. ROSAT (Röntgensatellit) observation revealed that the X-ray luminosity of the Algol binary system during the flared and quiescent phases is 2×10^{32} ergs^{-1} and 0.7×10^{31} ergs^{-1}, respectively [10,11]. Algol consists of a B-star and a sub-giant K-star. The B-star has a mass of 3.7 $M_{\odot}$, whereas the mass of the K-star is 0.81 $M_{\odot}$. The binary separation between these stars is 14.14 $R_{\odot}$, and their individual radius is about 2.9 $R_{\odot}$, and 3.5 $R_{\odot}$, respectively ($M_{\odot} = 1.988 \times 10^{30}$ kg, $R_{\odot} = 6.957 \times 10^{5}$ m; [9,12]). The B-star is in the main sequence phase, whereas the K-star is at the evolutionary stage and this can give rise to an Algol paradox. In the stellar evolution model, when the K-star fills its Roche lobe, most of its mass is transferred onto the B-star during accretion. The K-star has an active corona, and most of the X-ray emissions from the Algol binary system are contributed by the K-star [13,14]. The stellar flaring activities occur as a result of chromospheric and coronal activities, chromospheric evaporation. This generates magnetic activities that transport magnetic energy into the corona [10]. The stellar flares from Algol manifest with luminosities that last for a long duration, and this suggests that stellar flares from Algol belong to a class of "2-ribbons" or arcade stellar flares [15].

GRXE is an X-ray emission along the galactic plane with hard energy spectra in the range 2–10 keV as basic properties, and the emission lines from elements such as C, N, O, Ne, Mg, Si, Sr, Ar, Ca, and Fe have been observed in these energy spectra [16–19]. GRXE traces the distribution of stellar mass in the Milky Way. The integrated emission from faint galactic point sources explains the origin of GRXE, and each population source contributes different X-ray energy to the total luminosity of the GRXE [20–22]. Energy injection and confinement in the galactic plane is difficult to achieve [23–25]. Therefore, the origin of the GRXE cannot be explained by the diffuse source scenario. In the 6–7 keV energy range, the thermal iron emission line (Fe Kα line) is the prominent emission line among other line emissions observed in the galactic ridge [26]. This Fe Kα line was resolved into 6.4 keV, 6.7 keV, and 7.0 keV line emissions [19,22,27]. The 6.7 keV and 7.0 keV emission lines are broadening spectra while the 6.4 keV line emission has a narrow spectrum. The 6.4 keV line emission originates from the reflection of incident X-rays by cold gas [28], and it is consistent with the fluorescence of cool matter. The 6.7 keV and 7.0 keV GRXE are due to photo ionization/collisional excitation in the vicinities of the white dwarfs [29–31] associated with the numerous discrete/faint coronally active X-ray sources (discrete X-ray emitting objects). Some of the detected point sources (magnetic CVs; intermediate polars (IPs) and coronally active stars (ABs)) exhibit spectral morphology (shape) that is similar to the GRXE and Fe Kα line emission [22,26,28,30,32]. Recent research has shown that these stellar point sources contribute most of the Fe Kα line emission in the galactic ridge [28,30,33,34], but the total luminosity of the Fe Kα line of the GRXE has not been accounted for. Is there an additional galactic source whose spectral component could contribute to the total luminosity of the Fe Kα line of the GRXE? High mass X-ray binaries rather than CVs [26] and other yet to be identified galactic binary systems reside very close to the galactic plane and these galactic point sources can contribute to the total luminosity of the Fe Kα line of the GRXE.

In this work, we resolved a strong 6.7 keV line emission from the extracted stellar flare of Algol and found that the EW compares favorably with the EW of the 6.7 keV line emission from the galactic ridge. We are, therefore, suggesting that a collection of stellar flares in our galaxy, which emit such a 6.7 keV line, could account for the total luminosity of the 6.7 keV line from the GRXE.

2. Data acquisition

We retrieved the observed Algol stellar flare data used in this research work from the Suzaku data Public Archive. The observation of Algol's stellar flares was performed by X-ray imaging spectrometer (XIS) at the focal planes of the X-ray ray telescope (XRT) onboard the Suzaku satellite on 8–10 March 2007 with a net exposure time of about 170 ks. The XIS contains three functional sets of X-ray charge coupled device (CCD) camera systems (XIS 0, 1, and 3). XIS 0 and 3 have front-illuminated (FI) CCDs, while XIS 1 has a back-illuminated (BI) CCD. Details of the Suzaku satellite and the XRT and XIS of the Suzaku satellite are found in [35–37] respectively.

2.1. Data analysis

The spectroscopic data analysis of the extracted Algol stellar flares' was done using version 2.0 of the off-line standard Suzaku pipeline products and the tools provided in HEASoft version 6.10. The Algol flux was extracted from a circular region using 180 arc-seconds radius, and the extracted flux was saved. During the extraction, we ensured that the region covered about 90% of the Algol's flux. The background spectra (flux) were extracted from a circular region using 100 arc-seconds radius with no apparent sources, and we saved the extracted background flux. We subtracted the background spectra from the source spectra and generated the light-curve. We then extracted only the portion (between 40 and 90 ks of the light-curve; see the purple broken lines in Figure 1) where the Algol binary system showed stellar flares. The redistribution matrix file (RMF) and ancillary response file (ARF) were created for the XIS sensors (XIS 0, XIS 1, XIS 3) using the Flexible Image Transport System tools (FTOOLS), X-ray imaging spectrometer response matrix file generator (*xisrmf-gene*), and X-ray imaging spectrometer ancillary matrix response file generator (*xissamrf-gene*), respectively. We merged the spectral data of XIS 0 and 3, and referred to it as the XIS front illuminated (FI) spectrum. We referred to the XIS1 spectrum as the XIS back-illuminated (BI) spectrum.

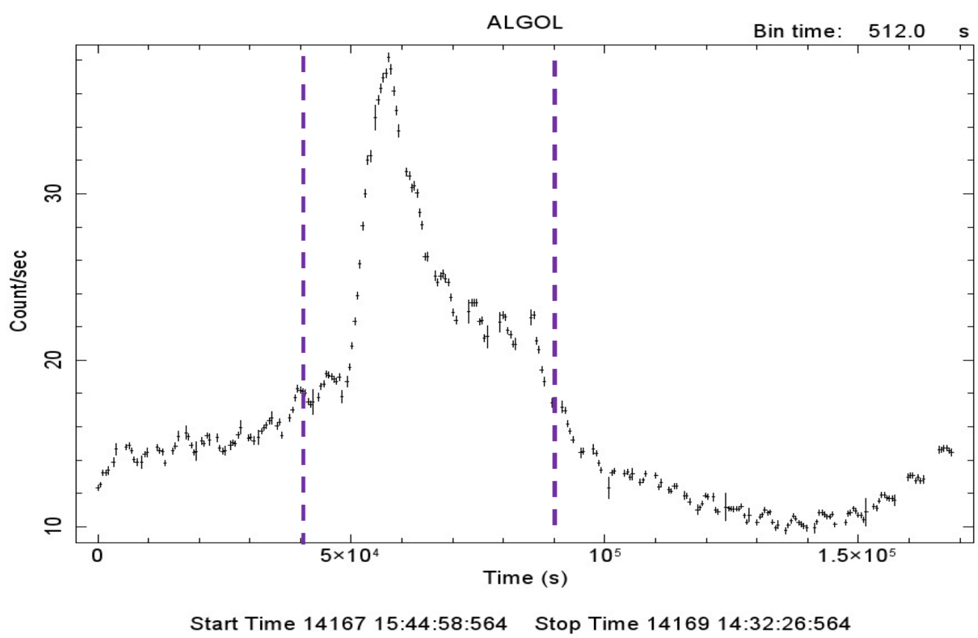

Figure 1. Background subtracted light-curve of the eclipsing Algol's stellar flares as a function of time during observation.

The spectral analysis was performed using XSPEC version 12.8. We modeled the spectrum using a thermal bremsstrahlung model with a Gaussian line. Our spectral fitting covers 4.5–7.5 keV for both the XIS FI and XIS BI. We were not able to measure the absorption (hydrogen column density, N_H) in full and partial covering matters due to low photon counts in the Algol's extracted stellar flares spectra and primarily to the 4.5 keV lower limits to our fits.

We also used power law plus one Gaussian line to mode the spectrum and got a statistically acceptable fit with similar EW value for the 6.7 keV line with the bremsstrahlung model.

We note that these hard X-rays creating the 6.7 keV lines via collisional excitation/ionization are generated during the flaring period in the corona of the star.

3. Results

Table 1 shows the best-fit spectral parameters and the errors in each parameter are estimated at the 90% confidence ranges, with reduced chi-squared (Rχ^2) value of 1.38 and 236 degrees of freedom, whereas Table 2 shows the power law fit parameters. Figure 1 shows the background subtracted light-curve of the Algol binary system. Figure 2 shows the resolved 6.7 keV emission line of stellar flares of the Algol binary system. The 6.7 keV emission line corresponds to the peak of the spectrum curve of both XIS FI and XIS BI.

Table 1. Algol binary system, bremsstrahlung spectral parameters.

Spectral parameter	Value	Unit
KT	3.61 $\pm$ 0.12	keV
F_{count}	(0.18 $\pm$ 0.01) $\times 10^{-3}$	Photons s^{-1} cm^{-2}
$E_{6.7}$	6.660 $\pm$ 0.003	keV
$EW_{6.7}$	510.18 $\pm$ 0.50	eV
R χ^2	1.38	-
d.o.f.	236	-

Table 2. Algol binary system power law fit parameters.

Power law fit parameter	Value	Unit
PP index	2.98 $\pm$ 0.02	-
F_{count}	(8.83 $\pm$ 0.03) $\times 10^{-3}$	Photons s^{-1} cm^{-2}
$E_{6.7}$	6.66 $\pm$ 0.01	keV
$F_{6.7}$	(15.83 $\pm$ 0.14) $\times 10^{-5}$	Photons s^{-1} cm^{-2}
$EW_{6.7}$	514	eV
R χ^2	1.38	-
d.o.f.	236	-

KT = continuum temperature, F_{count} = flux count, $E_{6.7}$ = Energy center of the 6.7 keV, $EW_{6.7}$ = equivalent width of 6.7 keV emission line, (R χ^2) = Reduced chi-squared value, d.o.f. = degrees of freedom.

4. Discussion of results

The light-curve of the Algol binary system shows a typical signature of a stellar flare. An inspection of the light curve shows that between 0 and 34 ks there is no significant change in the observed stellar flares. This is

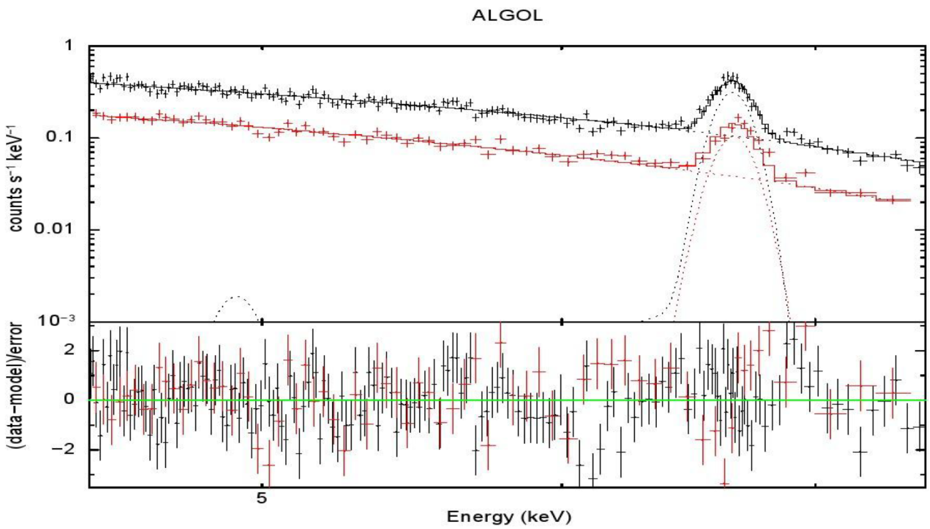

Figure 2. The upper panel shows spectrum of the eclipsing Algol binary system, while the data and the best-fit model are shown by crosses and solid lines respectively, and the peak of the spectrum is the 6.7 keV line as represented by dotted lines from the energy axis (black: XIS FI and red: XIS BI). The ratio of the data to the best-fit model is shown by crosses in the lower panel.

the quiescent phase of the observed stellar flares. The stellar flares rise gradually from 35 ks with a dramatic increase in brightness and reach their peak at 60 ks, and start decaying with a decrease in brightness. The stellar flares start to rise again at 150 ks for another cycle as the K-star rotates rapidly around the B-star. The 6.7 keV emission line is produced as a result of photo ionization/collisional excitation in the hot plasma. The bremsstrahlung model with a Gaussian line for the 6.7 keV emission line gave a statistically acceptable fit (see Table 1). We resolved 6.7 keV line emission from stellar flares of the Algol binary system, which is similar to the 6.7 keV line emission obtained from the galactic ridge.

We compared the equivalent width (EW = 510.18 eV) of the 6.7 keV line emission of Algol with that of the equivalent width of the 6.7 keV line emitted in the galactic ridge. We found that the equivalent width of Algol compares favorably with the equivalent widths (30–980 eV) of the 6.7 keV emission line obtained from different galactic plane/ridge regions [19,25,27,32]. Therefore, the Algol binary system might be among the probable galactic sources whose stellar flares contribute to the 6.7 keV GRXE.

4.1. Contribution of stellar flares from the Algol binary system to the 6.7 keV emission line from the galactic ridge

Our galaxy hosts luminous point sources, cataclysmic variables and active binaries (with an intrinsic X-ray luminosity range: 10^{30-33} ergs^{-1}), as plausible candidates for the origin of the 6.7 keV emission line because their large EW spectra are similar to the 6.7 keV spectrum observed in the galactic ridge [32,38], but these point sources have not completely explained the total luminosity of the 6.7 keV emission line. X-ray flaring stars and X-ray binaries (e.g., Algol) with the luminosity range 10^{30-33} ergs^{-1} could also be probable candidate sources that can contribute to the total luminosity of the 6.7 keV emission line.

In 2009, Revnivtsev et al. [22] resolved about 80% of the galactic ridge sources (473) detected by the Chandra Observatory in the energy range 0.5–7 keV into many points/discrete sources (accreting white dwarfs of luminosity; $L_{2-10\,keV} \sim 10^{31-32}$ $ergs^{-1}$, and binary stars with strong coronal activity; coronally active stars, of luminosity; $L_{2-10\,keV} < 10^{31}$ $ergs^{-1}$) of strong 6.7 keV line emission, but the study did not consider if stellar flares from other flaring stars and X-ray binaries (e.g., Algol) with luminosity range 10^{31-33} $ergs^{-1}$ are capable of generating the Fe Kα line on the galactic ridge. Stellar flares from RS Canum Venaticorum variables (RS CVn's), Algols, and other flare stars with luminosity range 10^{31-33} $ergs^{-1}$ generate a Fe Kα line similar to those of GRXE [39]. The stellar flares from Algol during the quiescent and the flaring phases have revealed high Fe abundant at the 6.7 keV line emission [9]. The photometric and spectroscopic analysis of cataclysmic variables (CVs), symbiotic stars, and X-ray active stars shows a strong Fe Kα line at 6.4 keV, 6.7 keV, and 7.0 keV [29,30,33,40], and the shape of the spectra of these sources resembles those of the GRXE. It is widely thought that these population sources are the major contributors to the Fe Kα line. The contributions of some of these point sources to the Fe Kα line in the galactic ridge have been estimated [33]. Warwick [34] reported that about 80% of the 6.7 keV and 7.0 keV emission lines of the GRXE are contributed by coronally active star and binaries (ASBs) and cataclysmic variables (CVs). Further argument by Warwick [34] suggested that X-ray emission from galactic X-ray binaries (XRBs) and young galactic stellar sources might contribute ~20% of the GRXE, and in view of this, Algol is an X-ray binary system. ASBs and CVs are considered as the major contributors to the Fe Kα emission line of the GRXE because of their higher population mass density, mass transfer rate, and hard spectra [30] when compared to other observed point sources. The contributions of hard X-ray emitting symbiotic stars [33,34,40] and other yet to be identified galactic point sources to the Fe Kα emission line in the galactic ridge are not negligible. The challenges we have now are that a large number of these point sources that could contribute to the uncounted Fe Kα emission line in the galactic ridge have not been observed by present X-ray telescopes. Moreover, Uchiyama et al. [38] were of the view that the equivalent width of the 6.7 keV line emission emitted by any point source is expected to be large. The equivalent width of the 6.7 keV line emission from point sources must be comparable to the equivalent width of the 6.7 keV emission line observed in the galactic plane/ridge [19,25,27,32].

In the present work, we discovered that the equivalent width of the Algol (Beta Persei), 510.18 eV, compares favorably with the equivalent width of the 6.7 keV GRXE in the range 300–980 eV depending on the galactic positions, and this implies that a collection of sources like Algol binaries are probable X-ray sources that may explain the total luminosity of the 6.7 keV emission line from the GRXE.

In order to determine the actual contribution of the 6.7 keV line emission of Algol and stars that flare to that of the GRXE, the procedure described previously [21,30,34,40,41] should be followed where the stellar density in the galaxy is taken into consideration in determining the total luminosity of the 6.7 keV line of the stars to be compared with that of the GRXE. This is beyond the scope of the present work, but Eze et al. (in preparation) will adequately address the issue.

5. Conclusion

We analyzed Algol's (Beta Persei) stellar flare data observed with Suzaku. The light-curve of the Algol binary system shows a typical signature of a stellar flare. We resolved the 6.7 keV emission line of stellar flares of the Algol binary system. The 6.7 keV emission line of stellar flares of Algol is similar to the 6.7 keV emission lines from the galactic ridge in different regions.

We observed that the equivalent width (EW) of the 6.7 keV emission line of the Algol binary system, 510 eV, compares favorably with the EW of the 6.7 keV emission lines from the galactic ridge. We are of the view that collection of similar systems (short period Algols; U Cep, TW Dra, RZ Cas, δ Lib, RW Ara, XZ Sgr, X Gru, V505, TV Cas, etc.) like the Algol (Beta Persei) and other flare stars could, along with CVs, hSSs, ABs, and ASBs, account for the total luminosity of the 6.7 keV emission line from the galactic ridge.

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