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FLARE X-RAY ACTIVITY OF THE γ CAS TYPE STAR HD 110432

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ABSTRACT

The X-ray light curves of the γ Cas type star HD 110432 (BZ Cru, B0.5IVpe) are analysed. In the present paper, the method for searching fast flares in the X-ray light curves proposed by Smith et al. (2012) is augmented and used to look for such flares from HD 110432 light curves with bin 5 s. The profiles, powers and numbers of flares in different energy ranges are examined. It has been established, that stellar X-ray light curve consist of fast flares and a base level without flares. We hypothesize that both mechanisms of flares generation proposed by Smith et al. (2012): accretion of disk matter onto a degenerate component and reconnection of magnetic field lines of the decretion disk and the star are effective for γ Cas type stars are effective.

Key words: stars: emission-line, Be – stars: binaries: individual: γ Cas – stars

1 INTRODUCTION

The enigmatic subclass of Be-stars named γ Cas analogues includes stars with power and hard X-rays. X-ray luminosity of such objects is higher than that of typical Be-stars, but lower than X-ray luminosity of high massive X-ray binaries. Assuming a completely thermal X-rays from γ Cas analogues, the temperature of the emitting plasma reaches 10-20 keV and even more. The first list of these objects is given by Smith et al. (2016a). Most of the γ Cas analogues are probably binaries with a low-mass companion (Naze et al. (2022)). Accordingly to Gies et al. (2023) γ Cas analogues are binary Be star accompanied by a white dwarf.

The formation of X-rays emitted by these mysterious stars is enigmatic and can, in a principle, be explained by following hypotheses:

1) An accretion onto a compact component, being either a neutron star in the propeller mode (Postnov et al. 2017) or a white dwarf (Gies et al. 2023);

2) an interaction between the magnetic field of the decretion disk and the local magnetic field of the star (Smith et al. 2016b);

3) the contribution of the possible non-thermal X-ray emission resulting from the inverse Compton scattering of UV photons by relativistic electrons in the framework of the Chen & White (1991) model as suggested by Ryspaeva & Kholtygin (2020, 2021)

According to the second scenario X-ray emission from γ Cas analogs should consist of a lot of the short flares. Smith et al. (2012) inspected this scenario on star HD 110432 (BZ Cru, B0.5IVpe) being the first discovered analog of γ Cas. Authors studied stellar light curves from the observations on *XMM-Newton* and *RXTE* satellites and revealed three kinds of X-ray variations of the object: long cycles of a few months, intermediate variations of a few hours, and rapid flares having lifetimes from 1.5 minutes down to several seconds. Authors found 1615 "fast flares" ("flare-like events").

Smith et al. (2012) explained these flares either by reconnecting the magnetic field lines of the decretion disk and of the star, or by accretion to a compact component. In the present paper we perform deeper investigation of X-ray fast flares on HD 110432. We use method by Smith et al. (2012) with our corrections and apply this for light curves with different steps and in various energy intervals. In addition, we test the hypothesis that fast flares, particularly those occurring at low energies, may be similar to solar nanoflares generated in the solar corona accordingly to (Cargill & Klimchuk 2006).

Present paper is organized by the following manner. Section 2 contain the detailed description of observational data reduction. The flares searching method is described in Section 3. The results of searching the fast flares in the X-ray light curves of HD 110432 are presented in Sections 4. General conclusions are given in Section 5.

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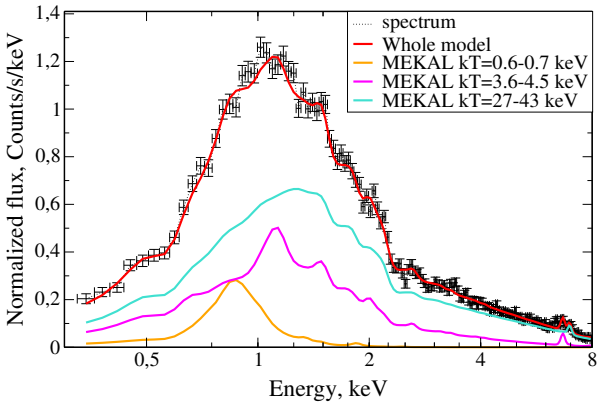

Figure 1. The best fit of X-ray spectra on September 4, 2007 by thermal models (thick red line). The contributions of individual model components are shown by other color lines.

2 OBSERVATION AND DATA REDUCTION

Log of observation of studied star is given in Table 1. X-ray luminosities for observations in 2002-2003 are taken from paper by Ryspaeva (2024). We reanalyzed archival X-ray observations, obtained by *European Photon Imaging Camera* (EPIC) onboard the *XMM-Newton* space observatory. We process data in *SAS v.20*[1] (Scientithic Analisys Software) package following the recommendations of the SAS team. The pipeline of observation data includes the *emproc* script for EPIC-MOS data and by the *epproc* script for EPIC-PN data. The filtration of the EPIC-images from background flares is performed with the *tabgtigen* and *esfilter* tasks. We convert times of EPIC-images from the local satellite frame to Barycentric Dynamical Time (TDB) whose spatial origin lies at the solar system barycenter by *barycen* task. The stellar light curves are extracted from filtered and baricentred EPIC-PN images.

This is done from the circle region with a radius of not less than 15′ centred on the stellar coordinates. They are taken from the SIMBAD[2] database and corrected for the X-ray image position. The background light curves are obtained from the regions of the same size in the places free of other bright sources. The background light curve correction is performed using the *epiclccorr* task. We extract light curves with binning 500-1000 s to reveal possible big flares. There are no big flares in examined light curves are found. The light curves with bin 5 s and 1 s in energy bands 0.2-10 keV, 0.2-1 keV, 1-2 keV, 2-4 keV, 4-8 keV are extracted for searching fast flares. We remove points with zero count rate and with errors more than count rates from these light curves.

In the present paper we analyse X-ray spectrum of HD 110432 from the observation on 4.09.2007 cited in Table. 1. The stellar and background spectra are extracted from the same regions on EPIC-images, as for light curve by *evselect*, *arfgen*, *rmfgen* tasks. The background spectrum correction is made using the *epicspeccombine* procedure.

[1] www.cosmos.esa.int/web/xmm-newton
[2] http://simbad.u-strasbg.fr/Simbad

Table 1. Log of observation. Fist column contains ObsID, observation dates and exposures are presented in 2nd and 3rd (in seconds) columns respectively. Observed X-ray luminosities (in 10^{32} erg s^{-1}) are given in the last column (see text)

ObsID	Date	Exposure	$L_X(0.2-8\,\mathrm{keV})$
109480101	3.07.2002	53046	8.77 ± 0.76
109480201	26.08.2002	48690	7.75 ± 1.03
109480401	21.01.2003	48015	7.39 ± 0.52
504730101	4.09.2007	80677	3.52 ± 0.05

Table 2. Parameters of fitting the spectrum from 4.09.2007 (see text).

Parameter	Value
kT_1, keV	$0.64^{+0.04}_{-0.04}$
$\log EM_1$, cm^{-3}	$53.71^{+0.08}_{-0.08}$
kT_2, keV	$4.1^{+0.4}_{-0.4}$
$\log EM_2$, cm^{-3}	$54.72^{+0.07}_{-0.07}$
kT_3, keV	$33.8^{+9.6}_{-6.9}$
$\log EM_3$, cm^{-3}	$55.15^{+0.02}_{-0.02}$
N_H, 10^{22} cm^{-2}	$0.226^{+0.007}_{-0.007}$
Abundance, sol. un.	$0.81^{+0.11}_{-0.10}$
χ^2 (d.o.f)	1.15 (475)

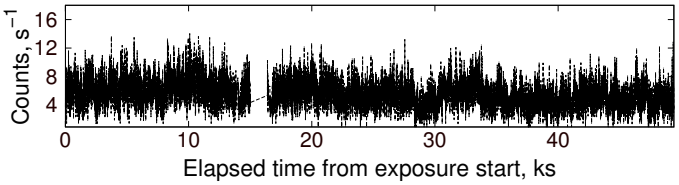

Figure 2. X-ray light curve of HD 110432 on July 3, 2002 (bin 5 s). The gap between 10 and 20 ks is caused by the removal a fragment with background emission flare.

Low-resolved stellar spectra from the EPIC images were fitted using the by three-temperature MEKAL model by Mewe et al. (1985, 1986) and Liedahl et al. (1995) in the XSPEC 12.10.0 package[3] for the 0.2-8 keV energy band. EPIC-PN, EPIC-MOS1, and EPIC-MOS2 spectra were fitted simultaneously. These models were multiplied on model TBABS by Wilms et al. (2000) describing the interstellar absorption.

Spectral fit parameters are presented in Table 2. For each thermal component the plasma temperature kT_i and the emission measures EM_i, where i is the component number. Stellar element abundance is given in solar units by Anders & Grevesse (1989). The good quality of the fit is confirmed to low value of the reduced χ^2 statistics also given in Table 2. The graphs of observed and model spectra are shown in Fig. 1. The temperatures kT_i and emission measures EM_i in the models for all remaining observations presented in Table 1 seems to be close to those given in Table 2.

As one can see in Fig. 1, the model spectra fits both the Fe K line complex at ∼6.4 keV and the lines of Hydrogen-like and the Helium-like Fe.

[3] https://heasarc.gsfc.nasa.gov/xanadu/xspec/

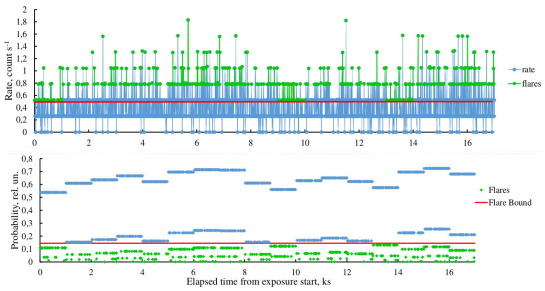

Figure 3. Illustration of looking for the flares in the light curves for the Poison distribution of counts. *Top panel*: the fragment of light curve, flare points are shown by green colour. *Bottom panel*: The probabilities of the registered counts in the same fragment. The red line shows the level above which points are considered as the flares.

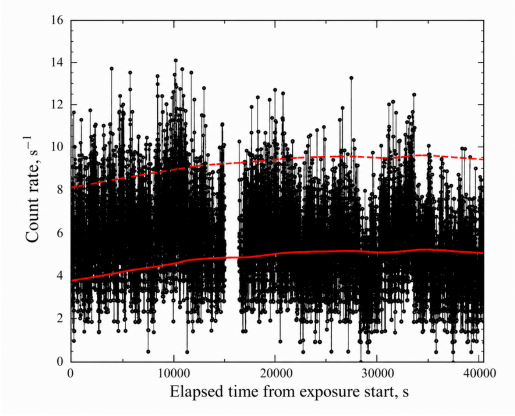

Figure 4. Illustration of searching the flares in the light curve on 3.07.2002, where the base level corresponds to the exponencial moving average of 1st order. This is shown by red line. The dashed red line shows the the exponencial moving average with additinal 2σ (see text).

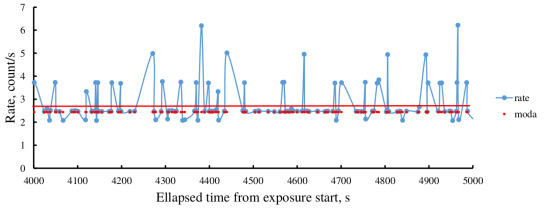

Figure 5. Illustration of searching the flares in the light curves, where the base level corresponds to the most common count rate (see text). Base level is marked by red points. Counts above the red line are supposed as belonging to flares.

3 FLARES IN THE X-RAY LIGHT CURVES

3.1 Flares detection

We propose that the total X-ray flux in some energy interval in light curve of the star can be presented as

$$F(E) = F_{\rm base}(E) + F_{\rm flare}(E), \qquad (1)$$

where $F_{\rm base}(E)$ is slowly varying base flux component. The

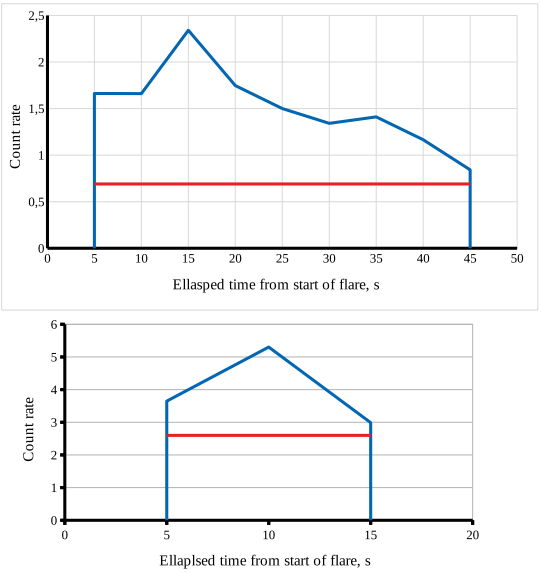

Figure 6. The examples of flares with simple profiles. Count rates are shown by blue lines, horizontal red lines show base count rate level.

second component $F_{\rm flare}(E)$ includes only flaring part of the X-ray flux.

Our analysis of the HD 10432 light curves with different bin values shows that the extraction of flaring events from the light curves is most efficient with a bin size of 5 seconds. Searching for fast flares in light curves with both smaller and large bins do not allow to investigate the exact profiles of the flares in the light curves. The typical light curve on July 3, 2002 with 5 s bin is illustrated in Fig. 2.

The methodic of flares extractions depends on the statistics of the X-ray counts. The light curve have been divided into intervals lasted about of 1 ks in which the base flux is supposed to be constant. For weak sources, one can assume that a number of counts in the light curve within each bin can be described by a Poisson statistics. The expected value of the number of arrived photons or parameter λ of the Poisson distribution of X-ray counts in the bin is estimated as the average value of counts in the interval 1 ks multiplied by the length of the bin in seconds. For the Poisson statistics we accept the level of counts corresponding to the parameter λ as the base level. Our numerical experiment for bins of 0.2 ks, 0.5 ks, 0.8 ks, and 2 ks have shown that the results of the flare detections practically do not changed for these bins in a comparison with bin of 1 ks.

Next, we fix the probability α defining whether the considered count number belongs to flare or not. If the registered count rate for a point in the light curve $R_{\rm flare} > R_\alpha$, where R_α is the count rate corresponding to the probability α, then it is supposed that the X-ray flare in that bin has occurred. Parameter α is estimated supposing that the number of false-positive rates do not exceed 10%.

For the light curves with high count rates we can consider the 1st order exponential moving average as the base level.

The points exceeding this level by 2 standard deviations σ are considered as flares as it is demonstrated in Figure 4.

In some light curves, the base level is visible by eye. For these curves we consider the mode of the distribution as the base level. The points in the curve with count rates above the 1.1 of the base level are considered as flares. Figure 5 illustrates this case.

Flare points can be either isolated or be the groups of adjacent points without gaps between them. Both isolated flare points and groups of such points we consider as the separate flares (flare events). The detected flares have very different shapes, examples of which are shown in Figs. 6 and 7. We classify three types of flares: the ultrafast consisting one flare point only; the simple including the group of flare points without local minima; and the combined, which are also the group of such points but with at least one deep local minima within the profile. The latter most likely can be superimposing of several shorter flares.

We introduce next criterion for identifying the combined flares:

$$\frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} > 0.3, \qquad (2)$$

where $R_{\max}$ and $R_{\min}$ are the biggest and the smallest count rate in the flare profile respectively. The combined flares can be presented as a combination of the shorter subflares. Local minima probably separate individual sub-flares contributed in the combined flare as it shown in Fig 7. But we should keep in mind the different possibilities to divide the combined flare onto the individual sub-flares.

According to our preliminary suggestion on an analogy the stellar with solar nanoflares, all fast X-ray flares should have similar shapes. From the above described analysis and examples of flares shown in Figs. 6 and 7 one can conclude that this suggestion is probably wrong.

3.2 Parameters of flares

For each flare we estimate the following characteristics: duration (in seconds), integral power and relative power. For all of the considered light curves the total numbers of flares and relative contribution of flares in whole X-ray stellar flux are calculated.

The integral power of flare in units of detector counts is determined by next expression:

$$P_{\text{flare}} = \frac{1}{2} h \cdot \sum_{i=1}^{N-1} (R_i + R_{i+1}), \qquad (3)$$

where R_i is a flare count rate for the time interval with a number i, N is a full number of counts within a flare, and h is the bin size (time interval between subsequent flare counts).

The relative power of flare is calculated as a ratio

$$Q_{\text{flare}} = \frac{P_{\text{flare}} - P_{\text{base}}}{P_{\text{base}}}. \qquad (4)$$

Here P_{base} is a sum of the counts of the base level for all bins corresponding to the flare.

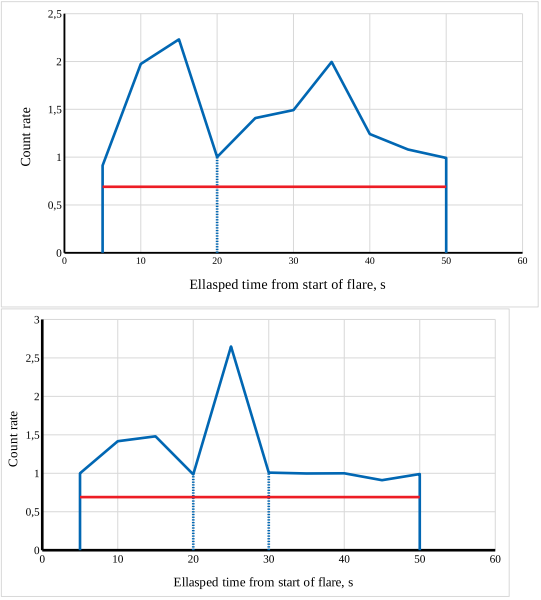

Figure 7. The same as in Fig. 6, but for combined flares. Vertical dashed lines indicate the division of the flare into subflares.

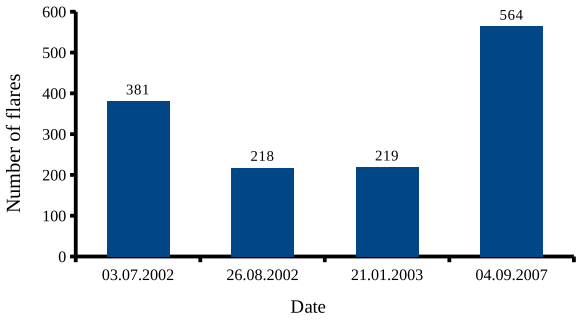

Figure 8. Numbers of flares in light curves for $0.2-10$ keV energy band with 5 s bin.

For each individual observations the fraction of the flares contribution into the full stellar X-ray flux is estimated as

$$f_{\text{flare}} = \frac{\sum_{k=1}^{M} P^k_{\text{flare}}}{P_{\text{LC}}}, \qquad (5)$$

where M is the number of flares in the light curve, P^k_{flare} is the power of flare with number k, and P_{LC} is an integral power of the whole Light Curve, which is the sum of all counts registered during the considered observation.

Our calculations show that from tens to thousands of fast flares with various integral powers and durations are registered for each of the analysed light curves corresponding the observation cited in Table 1.

Ultrafast flares were not taken into account by Smith et al. (2012) and need special consideration. Such flares make up a large part of all fares. We will consider ultrafast flares with $Q_{\text{flare}} > 0.8$ only.

This inequality corresponds to the condition $P_{\text{flare}} > 1.8 P_{\text{base}}$. Our numerical experiment shows that this condi-

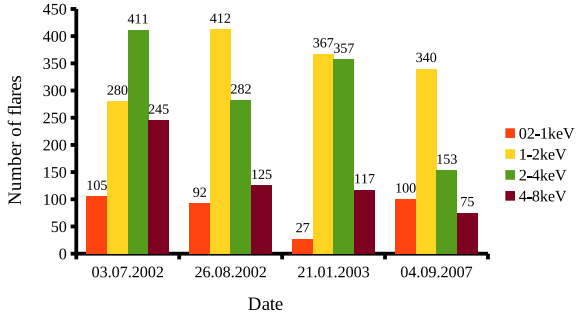

Figure 9. Numbers of flares in the light curve for different energy intervals.

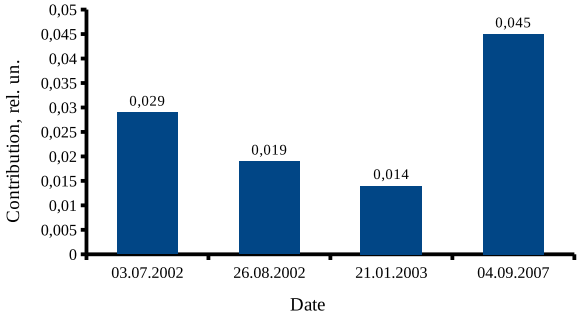

Figure 11. Contributions of flares in the X-ray light curves for different observations.

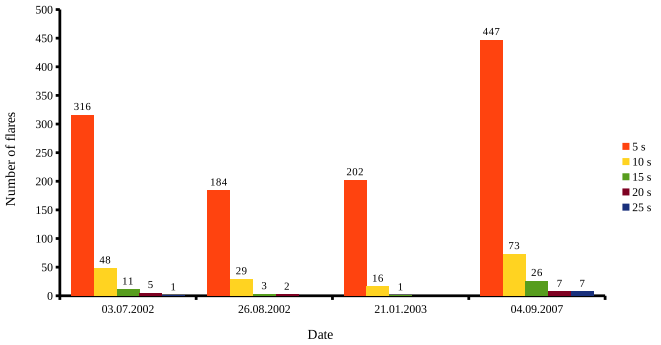

Figure 10. Numbers of flares in the light curves in the full 0.2-10 keV energy band with durations from 5 s to 25 s.

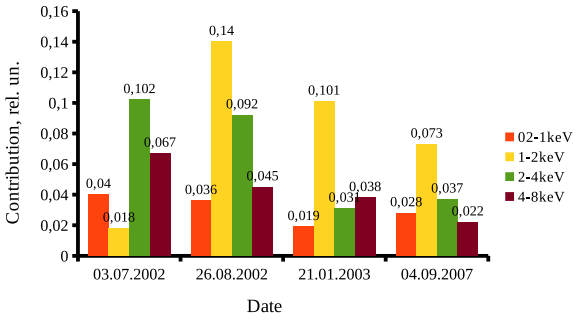

Figure 12. Contributions of flares in the total X-ray light curves energy for different energy bands.

tion allows us to identify the majority of flare events with a false-positive rate do not exceeding 1%.

4 RESULTS

Fig. 8, demonstrate the numbers of fast flares in the total energy interval $[0.2 - 10]$ keV detected for four observations of HD 110432 with using the procedure described in subsection 3.1.

In Fig. 9 the numbers of flares in different energy bands are given. In the light curves for all observations many fast flares appears to be combined with the small local minima. Durations of these flares reach 55 s. At the same time the larger part of flares extracted from the light curves seems to be simple. There are very small number of flares with durations up to 25 s. (see Fig. 10).

All registered flares in the light curves have a wide range of integral powers from 1 to 289 counts. The most of flares extracted from the light curves looks like a superposition of shorter flares. The relative powers of the flares including two and more flare points have relative powers $Q_{\rm flare}$ up to 0.2 rel. un.

As mentioned above, the temperature of the X-ray emitted plasma remained practically do not changed though X-ray luminosity of star reduced from 2002 to 2007. Our searching the fast X-ray flares evidenced the decreasing of the X-ray luminosity of HD 110432 leads to reducing the number and contribution of fast flares only in 4-8 keV X-ray interval. Numbers and contributions of flares in whole examined range 0.2-10 keV and other narrow ranges do not depend on stellar X-ray luminosity or emitted plasma temperature.

Fig 11 show the contribution of the flares in total X-ray flux emitted during the considered observation for different dates. This parameter can reach only 4.5% for the observation with the lowest X-ray luminosity. In Fig 12 the same value is plotted, but for different energy bands. The fractions of flares in the bands are decreased with X-ray luminosity excluding the case of soft $[0.2 - 1]$ keV band.

5 CONCLUSIONS

The contribution of fast flares in the total X-ray luminosity is rather small as it is seen on figures 11 and 12. This result is in favor of the hypothesis about the interaction between the magnetic fields of the decretion disk and the local magnetic fields of the star. Most probably the X-ray light curves contain both fast flares and a slowly changing base level without flares.

The nature of the base level is not entirely clear. In binary γ Cas analogues, this part of the X-ray fluxes can be resulted from the accretion of the matter of decretion disk onto a compact component. The contribution of the non-thermal component to the spectrum of HD 110432 is still possible but remains unproven.

Our analysis demonstrates that fast flares predominate at energies of 1-4 keV. This means that they are most probably not similar to solar nanoflares. We may suppose that the changes in the mass and density of the HD 110432 decretion disk affect the features of the star's X-rays. The proposed method for detecting fast flares in the X-ray light curves can be used to analyse the X-ray light curves of not only γ Cas analogs, but those of other astrophysical objects.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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