Small-scale flare activity on YZ CMi

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Abstract. The results of the photometric analysis of two flares are presented on the red dwarf YZ CMi. The data was obtained in March 2007 and October 2012 during monitoring with the Zeiss 2000 telescope at the Observatory at Peak Terskol. These observations revealed the presence of small scale high-frequency oscillations (HFO) in a calm state of a star, previously discovered during outbursts by Zhilyaev et al. (2000), and then confirmed by Contadakis et al. (2004). The amplitude-frequency characteristics of HFO are discussed. To search for periodicities in the calm state, we used the Fourier transform to clean the harmonic with a high signal-to-noise ratio on the star's light curve. After the cleaning procedures, we can see small-scale HFO, which exceed instrumental errors. We found periodic pilot signals on YZ CMi, which control the flares of a star. Their amplitude is small, several hundredths of a magnitude in U-rays. We demonstrate that both large and small flares appear at the highs of the pilot signals. Thus, we conclude that a star flare activity is not random, but a certain deterministic process. This effect is a new phenomenon that is not taken into account in modern theories of stellar flares.

Key words: stars: activity – stars: flare – stars: chromospheres – methods: observational –

Introduction

The red dwarf YZ CMi (dM 4.5e, $U = 12.9$, $B = 12.7$, $V = 11.1$, $R = 0.36\,R_{\odot}$, $M = 0.34\,M_{\odot}$, $T = 2900$) is one of the brightest and most active flare stars. It is also an object of many studies. According to the Crimean Catalogue of flare stars (Gershberg 2005), optical photometry of this star during flares is given in 164 papers, optical spectra are presented in 55 articles, and X-ray spectra and UV observations are presented in 49 and 25 publications, respectively.

Zhilyaev et al. (2011) performed a detailed analysis of the fine temporal structure of the flare on YZ CMi, observed from the Peak Terskol on February 9, 2008 in U band. The flare was the most powerful compared to 325 other, previously discovered on this star. Wavelet analysis applied to the pulsed phase of the flare, revealed damped quasi-periodic oscillations with period $T_p \approx 11$ sec. Based on the solar-stellar analogy, the main parameters of flare loops were determined using calculation formulas obtained by Stepanov et al. (2005), suggesting that the observed pulsations were associated with radial vibrations of fast magnetoacoustic (FMA) modes. The following parameters were determined in the field of energy release using the methods of coronal seismology: the concentration of particles in the plasma is $2 \cdot 10^{10}$ cm^{-3}, the temperature is $3 \cdot 10^{7}$ K and magnetic field strength is 0.015 T.

Spectrophotometry of YZ CMi was carried out at the Observatory at Peak Terskol with a low-resolution spectrograph with the spectral resolution ~ 100 Å and time-resolution from 2 to 30 seconds (Verlyuk 2016). The spectra of the star in a calm state showed variability in the H_{β}, H_{γ}, $Mg\,b$, and, possibly, in Ca II K + H_{ϵ}. Variations in equivalent widths of the order of a few percent were discovered. The characteristic time of the variation was about few minutes. The observed variations indicate non-stationary activity of the star's atmosphere at rest. The Fourier power spectrum and the global wavelet power spectrum of YZ CMi show oscillations with a period of 30 to 70 seconds. We can estimate the average period of oscillations around 50 seconds. The relative amplitude of the oscillations is $\triangle I/I \approx 2.2$ %.

Below we consider the results of the observations, focusing on the analysis of the temporal structure of the intensity of the star, both in a calm state and in time of flare events using the Fourier transform. We also estimate the main parameters of flare loops based on the solar-stellar analogy, using the method proposed by Stepanov et al. (2005).

Observations and data processing

YZ CMi flares were observed on March 14, 2007, and October 17, 2012, in the U band with the help of the 2-m Richie-Chretien telescope (Peak Terskol, North Caucasus) with a fast two-channel UVBR photometer (Zhilyaev et al. 1992). The signal integration time was up to 0.1 s. The sky background was subtracted from the data. UBVR observations were converted to the magnitude scale.

To clean the light curves from atmospheric variations, we used the data of the reference channel of the photometer with a comparison star. Raw light curves are shown in Fig. 1. The light curves cleaned with the help of a comparison star in the reference channel of the photometer are presented in Fig. 2, 3.

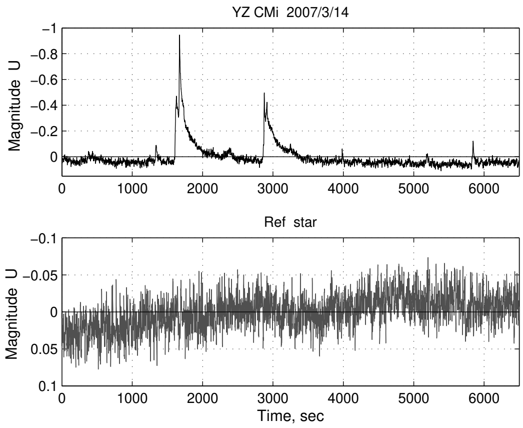

Fig. 1. Light curves of YZ CMi and a comparison star on March 14, 2007

Intensity variations with a period of oscillation of about 200 sec can be seen on the flare light curve of the YZ CMi on October 17, 2012 (Fig. 2).

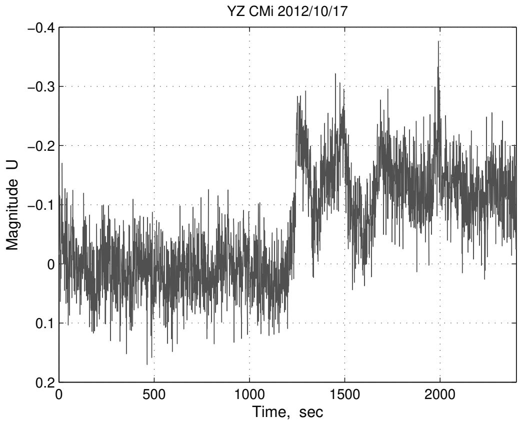

Fig. 2. YZ CMi flare on October 17, 2012.

Fig. 3 shows a fragment of the light curve of the YZ CMi flare on March 14, 2007 (thick curve) and the reconstructed pilot signal (thin curve).

We use the term "pilot signal" similarly to telecommunications, where a pilot signal is usually a signal of a single frequency transmitted over a communications system for supervisory, control, synchronization, or reference purposes.

Note that the pilot signal (PS) is usually not visible due to the small signal-to-noise ratio. For the detection of PS, the light curve is preferably pre-cleaned from the components in the power spectrum with a large signal-to-noise ratio. We clean the light curve using the Fourier transform. A cleaned light curve usually easily demonstrates the pilot signal. It is easy to see it in the spectrum in Fig. 4 (peak at the frequency of 0.00725 Hz, period 138 s).

Many time series can contain a red noise component. We estimate the red-noise component in the power spectrum using the technique given in the paper by Torrence & Compo (1998). We use a simple model for red noise as the unvaried lag-1 autoregressive or Markov process:

$$X_n = \alpha \cdot X_{n-1} + Z_n$$

where α is the assumed lag-1 autocorrelation and Z_n is the original data which have been "whitened" for all periodicities that dominate in the spectrum. After that, we have the Markov red noise spectrum (red continuum) for the selected value of α. The significance of a peak is determined by comparing its amplitude to the amplitude of the red continuum. The solid curve shows the red noise continuum in Fig. 4.

Fig. 5 shows a fragment of the light curve in the regions of maxima of large flares of YZ CMi on March 14, 2007, with the pilot signal (thin curve). Fig. 3, 5 give a clear idea that the flares, both small and large, provoke the pilot signsl's leading edge. In Fig. 6 you can see the YZ CMi flare on October 17, 2012. The flare and the high-frequency fluctuations in it are synchronized by the pilot signal, which is the sum of two harmonics with periods of about 200 and 104 seconds. The pilot signal is enlarged for clarity.

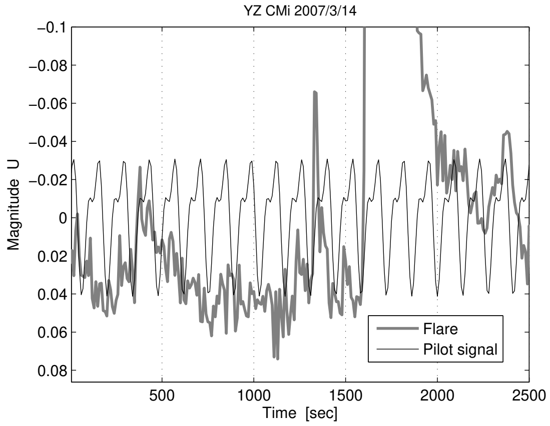

Fig. 3. Fragment of the light curve of the YZ CMi flare on March 14, 2007 (thick curve) and the pilot signal (thin curve).

Properties of high-frequency oscillations in flares

Flare intensity oscillations were first detected on the star EV Lac at the beginning of 2000 (Zhilyaev et al. 2000). Radiation ripples were interpreted as a result of fast magnetoacoustic vibrations of coronal loops (Kouprianova et al. 2004, Stepanov et al. 2005). The theory makes it possible to evaluate the features of the coronal loops (temperature, electronic concentration, characteristic dimensions) using the numerical values of the characteristics of the intensity oscillations. To estimate the characteristics of the high-frequency signal in the observational data, we used the wavelet transform method. The primary functions used in the wavelet transform are localized not only in the frequency domain but also in the time domain. It means that wavelet analysis is more suitable for studying the unsteady process than the harmonic Fourier method. The first allows identifying both high-frequency and low-frequency characteristics of the signal and observe their changes in time, creating the corresponding spectral functions in the time-frequency space.

The high-frequency component of the YZ CMi light curve on October 17, 2012 reconstructed using wavelet filtering methods (Zhilyaev et al. 2011) in the interval of periods T_p = 157 - 284 s is shown in Fig. 7. The bold line is a decaying cosine curve with a period of oscillations 266 ± 51 s and

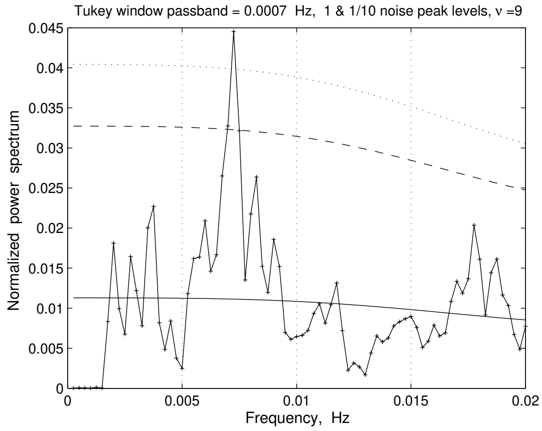

Fig. 4. Normalized power spectrum of the cleaned light curve with the pilot signal on frequency 0.00725 Hz, period 138 s. The solid curve shows the red noise continuum, dotted curves show 95% and 99% confidence detection boundaries.

exponential decay time of 667 s. The relative amplitude at the maximum of the flare (modulation depth) is $\triangle I/I \approx 5.5\%$.

The high-frequency component of the YZ CMi light curve observed on March 14, 2007, reconstructed in the interval of periods T_p = 48 - 67 s is shown in Fig. 8. Bold line presets a decaying cosine curve with a period of oscillation of 54.4 ± 4.5 s and exponential decay time of 159 s. The relative amplitude at the maximum of the flare is $\triangle I/I \approx 6.0\%$.

Additionally, the 95% detection boundary is shown in Figs. 7, 8 for the signal after wavelet filtering according to the technique given in the paper by Torrence & Compo (1998). As a result, we can see several peaks of the signal.

Diagnostics of coronal plasma

To estimate the main parameters of the flare plasma and magnetic field, we use the solar-stellar analogy, and a diagnostic method developed, taking into consideration the characteristics of dispersion, excitation, and attenuation of eigen modes of vibration of magnetic tubes. Key assumptions of the models proposed by Stepanov et al. (2005) are as follows. The coronal loop can be presented in the form of a cylinder with firmly fixed bottoms. A sharp increase in gas pressure in an outburst can cause fast magneto acoustic (FMA) modes, the period of which is determined by tube cross-section a. If the coronal arc acts as a magnetic trap and can collect charged particles, the FMA oscillations will lead to accelerated particle flux modulation in the chromosphere and photosphere due to a change in coefficient stuck. The heating of particles leads to the observed pulsations of the optical radiation.

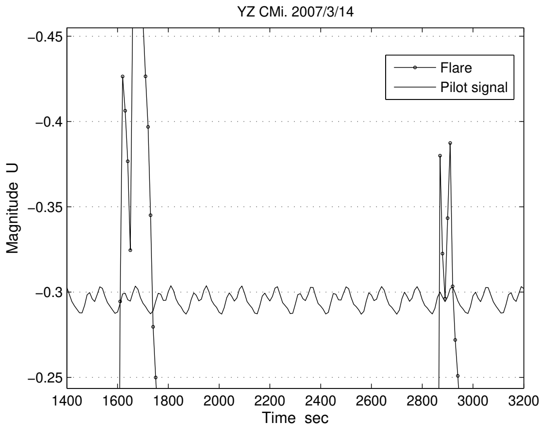

Fig. 5. Fragment of the light curve in the region of the maxima of the large YZ CMi flares on March 14 2007 with the pilot signal (thin curve).

In terms of the scenario described by Stepanov et al. (2005), we give formulas for estimating temperature T, particle concentration n and magnetic field B in the contour of the flare, using the following parameters of radiation oscillations: period T_p, modulation depth M, Q factor $Q = 2\pi\tau/T_p$, a and L - radius and length of the magnetic tube.

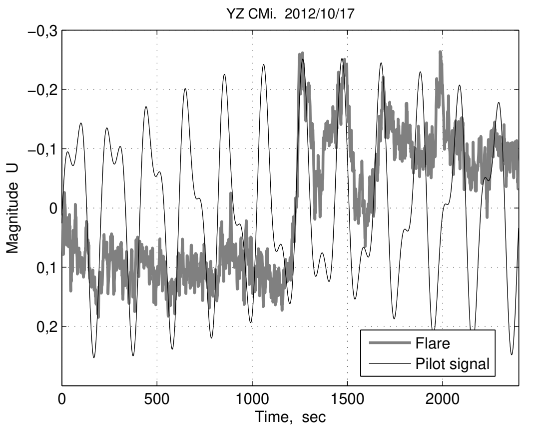

Fig. 6. YZ CMi flare on October 17, 2012. The pilot-scale has been enlarged for convenience.

The approach of Stepanov et al. (2005) made it possible to obtain relations for determining parameters of flare plasma in the coronal loop:

$$
\begin{aligned}
T &\approx 2.4 \times 10^{-8} \frac{\tilde{r}^2 M}{T_p^2 \chi} \ \ [K], \\
n &\approx 1.97 \times 10^{-12} \frac{\tilde{r}^3 \tilde{\kappa} M^{5/2} Q \sin^2 \theta}{T_p^4 \chi^{3/2}} \ \ [\mathrm{cm}^{-3}], \\
B &\approx 9.06 \times 10^{-18} \frac{Q^{1/2} \tilde{r}^{5/2} \tilde{\kappa}^{1/2} M^{5/4} \sin \theta}{T_p^3 \chi^{5/4}} \ \ [\mathrm{G}].
\end{aligned} \tag{1}
$$

where $\theta \approx \mathrm{arctg}(\eta_0 a/\pi L)$ is the angle between the FMA wave vector $\mathbf{k}$ and the magnetic field $\mathbf{B}$, $\tilde{r} = 2\pi a/\eta_0$, $\eta_0 \approx 2.4$, $\chi = 20/3M + 2$, $\tilde{\kappa} = 486M \cos^2 \theta + 1$.

The quality factor Q is a parameter of the oscillatory system, which characterizes a loss of energy when the phase increases by 1 radian. Let the quantity $x(t)$ change over time, like:

$$x(t) = Ae^{-\beta t} \cos \omega t$$

where $A = x(0)$ is the initial amplitude, t is time, $\omega = 2\pi/T_p$ is the cyclic frequency, T_p is a period of oscillations. Denote $x_k = x(kT_p)$, hence we obtain that the quantities x_k and x_{k+1} are

$$\lambda = \frac{1}{n} \ln(x_k/x_{k+1}) = \ln e^{\beta T_p} = \beta T_p$$

Logarithmic decrement (damping coefficient) λ is equal to exhibitors. The Q factor is related to the logarithmic decrement λ by the relation

$$Q = \frac{2\pi}{1 - e^{-\lambda}}$$

To determine the value of Q, we calculate the logarithmic decrement λ according to the formula

$$\lambda = \frac{1}{n} \ln \frac{x(t)}{x(t + nT_p)}$$

where n is an integer of positive peaks.

Below are given the results of observations of flares on YZ CMi. Assuming an aspect ratio of 0.25 (often seen in solar flares), and $a = 5 \cdot 10^9$ cm, a loop length of $L = 2.0 \cdot 10^{10}$ cm can be derived. Taking the values Tp, M, Q, given above, we obtain the values of temperature, the concentration of particles and magnetic field strength in the plasma of the coronal loop. For the flare on 2007/03/14 these are: $T \approx 9.7 \cdot 10^7$ K, $n \approx 1.4 \cdot 10^{11}$ cm $^{-3}$, $B \approx 614$ G.

The strong dependence of plasma characteristics on the value of the radius of the loop a according to formulas (1)should be noted, given plasma characteristics are calculated for $a = 5 \cdot 10^9$ cm, which is about 20% of the radius of the star. When $a = 1 \cdot 10^9$ cm, the plasma characteristics decrease by one or two orders of magnitude, which gives implausible loop parameters.

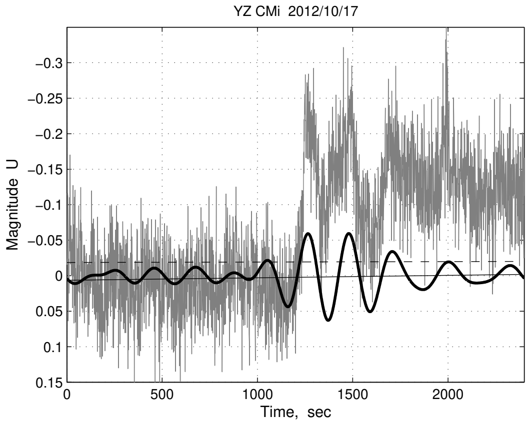

Fig. 7. YZ CMi flares on October 17, 2012. The HFO curve is highlighted in bold.

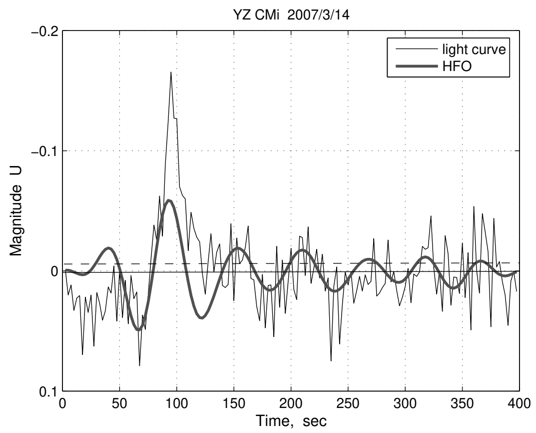

Fig. 8. YZ CMi flares on March 14, 2007. The HFO curve is highlighted in bold.

Conclusion

The results of the photometric analysis of two flares on the red dwarf YZ CMi are presented. Outbursts were observed in March 2007 and in October 2012 in the U band using the 2-m Ritchie-Chretien telescope at the Observatory on Peak Terskol. We found periodic pilot signals that control the flare light curves of YZ CMi. Their amplitude is small, a few hundredths of a magnitude in U-rays.

We show that both large and small flares appear at highs of pilot signals. The pilot signal is usually not visible due to the low signal-to-noise ratio. We clean the light curve of components in the power spectrum with a large signal-to-noise ratio using the Fourier transform. In a cleaned light curve, it is usually easy to detect a pilot signal. The figures above give a clear idea that flares, both small and large, provoke a leading edge of the pilot signal. We conclude that the flare activity of a star is not random, but a specific determined process. This effect is a new phenomenon that is not taken into consideration in modern theories of stellar flares. We estimate the main parameters of small-scale YZ CMi flares based on solar-stellar analogy, using the model proposed by Stepanov et al. (2005).

According to the proposed model, the flare excites fast radial magneto-acoustic vibrations in the coronal loop. We estimate the temperature T, the particle concentration n, and the field B in the flare circuit using the following vibration parameters: period T_p, modulation depth M, Q factor $Q = 2\pi\tau/T_p$, a and L - radius and the length of the magnetic tube. Taking into account the results of observations of flares on YZ CMi, we obtain the values of temperature, particle concentration, and magnetic field strength in the coronal plasma. For the flare on 2007/03/14: $T \approx 9.7 \cdot 10^7$ K, $n \approx 1.4 \cdot 10^{11}$ cm $^{-3}$, $B \approx 614$ G.

The plasma characteristics given are estimates and are rather of a demonstrative nature, since it is impossible to obtain from photometric data the value of the radius of the coronal loop, on which the estimates of the characteristics of the plasma in the coronal loop depend substantially.

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