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Quasi-periodic pulsations in flares of UV Ceti-type stars

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Abstract. Quasi-periodic pulsations (QPPs) were observed in the light curves of solar and stellar flares. The number of stellar QPP events is quite small (213 in 2021), which is why they are interesting. QPPs can be used to investigate the properties of flare regions and they are still a problem for flare models. QPPs were identified in stellar flares across a wide range of wavelengths, from radio to X-rays. In the optical band they are searched mainly in the Kepler and TESS data. The periods of QPPs detected from these sources are longer (tens of minutes) than from the high cadence data. Observations with the 6-m telescope BTA and the MANIA complex, as well as the space observatory GALEX, reveal QPP periods of only tens of seconds. On the other hand, solar flares are typically weaker (energies $\ll 10^{32}$ erg) than stellar flares, that possibly makes them more difficult to detect in white light. Our data on 157 flares of dM-type stars (EV Lac, Wolf 359, Wolf 424, V577 Mon, and UV Ceti), obtained from 70 hours of observations with the BTA telescope in U-band with microsecond time resolution, represents a significant breakthrough in the search for QPPs in stars. In this paper, we present the characteristics of 13 QPPs found in 44 flares. The QPPs have periods ranging from 6 to 107 seconds, and were identified using both Fourier transform and empirical mode decomposition methods. We classify the observed QPPs based on the evolution of their oscillation envelopes and fractional flux amplitudes.

Keywords: stars: flares, oscillations, low-mass

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1 Observations and data reduction

We conducted an observation campaign with the MANIA complex (Plokhotnichenko et al. 2021) on the 6-m telescope BTA for the search of M dwarfs flares. A significant number of observed flares show QPPs. To analyze the flare light curves for periodic signals, we used two independent methods: Fourier transform and the EMD. The latter applied to QPPs is extensively used, e.g. Doyle et al. (2018).

2 Results

Figure 1 shows some off-trend light curves from 13 flares, where a pulsating component is visible (we note that QPPs 11 and 12 correspond to the middle and the end of the same flare, respectivelly) and modeled by the EMD oscillation modes as shown by blue line. Their periods P_{QPP} range from 6 to 107 seconds, as seen in Table 1, and they have statistical significance of at least 1σ in Fourier and 2σ in EMD analysis. One can see in Fig. 1 the QPPs evolve in a flare, while the solar QPPs are mainly of narrow band periodicity. There are multiperiodical QPPs, some of which could be multiple.

3 Discussion and conclusions

At a rough guess these QPPs could be differentiated as decaying (QPPs 1, 12 and 14 shown on the left column of Fig. 1), decayless (8, 10, 11 and 13, highlighted on the right column) and transitional among each other (2–7 and 9, highlighted on the central column). By doing so, the first pulse, at flare maximum, is not accounted, because it is as rule distinguished from the others. Its steep amplitude, narrow width or large precedence time are not compliant with an exponentially decaying oscillation. It clearly does not belong to the followed wave train, i.e. has a diffent origin. In some cases it looks like a result of the superposition of several waves different in phase and period as in QPP 1, where the superposition appears also in the wide band saw-like pulses. Such superposition is awaited for stellar flares which are not spatially resolved and the source of QPPs is a bunch of oscillating coronal loops. The oscillations in the decayless parts of some QPPs (e.g., 9, 11 and 13) are amplitude modulated, which also indicates the superposition. In QPP 5 the first half-wave is an artefact of the detrending and three spikes are overlaid on the following wave, which corresponds to the flare maximum. The first wave of QPP 1 is also spiked.

In total, there are three components in all these QPPs: the first one is a possibly spiked pulse detached from the following wave train, the quick decay within 2–3 waves and quasi-decayless oscillation, possibly amplitude-modulated. Such QPP pattern

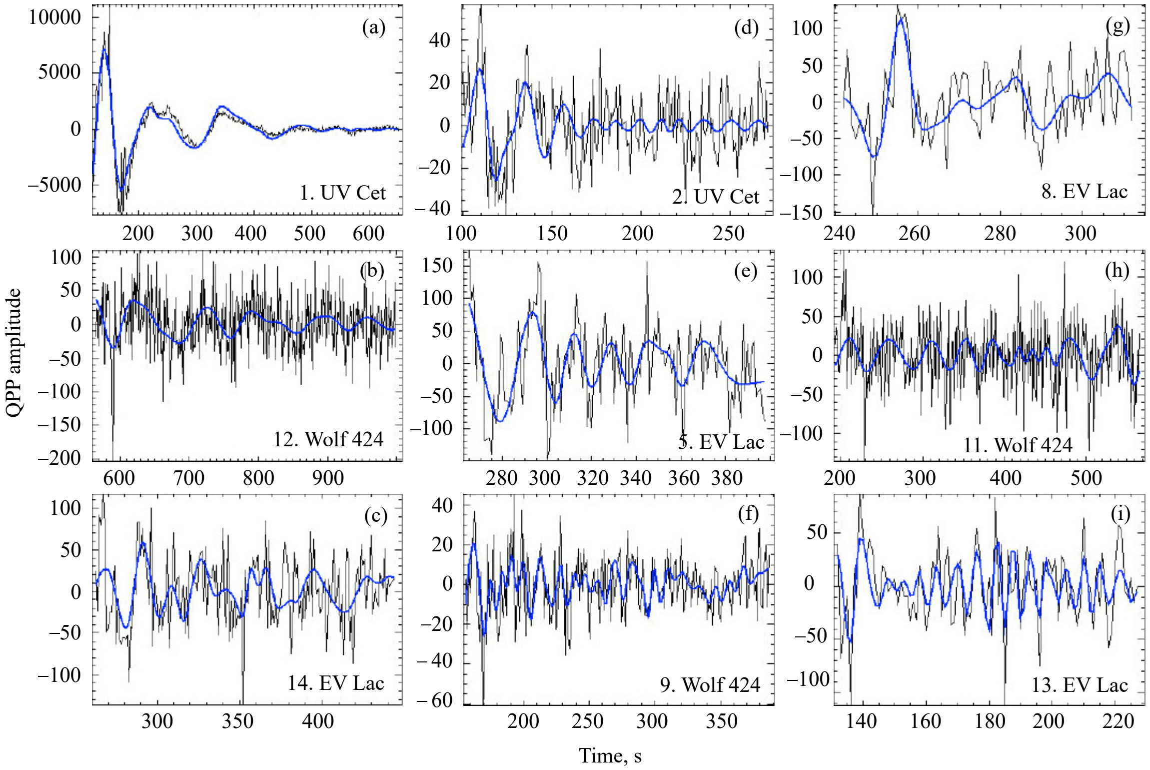

Fig. 1. The oscillating components of flares of M dwarfs EV Lac, Wolf 424 and UV Ceti with superposed model of the EMD oscillation modes by blue line. QPP number in Table 1 precedes the star name on graphs. The transition from decaying to decayless QPPs takes place from the left to the right columns. Time and QPP amplitude along the axes are in arbitrary units.

looks like an imprint of the sequence of MHD events similar to the Sun flare observed by Nisticó et al. (2014), where a quasi-periodic fast (> 1000 km/s) quasi-decayless (≥ 10 wave fronts) wave trains propagate away from a shot of flare region.

The connection between the time characteristics of QPP and energetics of flare is an intriguing question. The fractional flux amplitudes of the QPPs, $A_{\rm QPP} = \Delta F_{\rm QPP}/F_{\rm trend}$ for the second QPP pulse, and flares, $A_{\rm fl} = \Delta F_{\rm flare}/F_{\rm quiescent\,star}$, are in the intervals 0.02–0.13 and 0.2–14.4, the latter corresponding to stellar brightening of $\Delta m_U = 0.2$–3.0 mag. The bolometric energy of a flare is estimated as $E_{\rm fl} = W_{\rm t} L_{\rm bol} \kappa_{\rm s}/\kappa_{\rm f} \eta$, where $W_{\rm t}$ is the equivalent duration of flare (ongoing with the quiescent stellar flux, we should also note its difference from flare duration, $\Delta t_{\rm fl}$), $L_{\rm bol}$ the quiescent star bolometric luminosity, κ the fraction of blackbody flux (determined by the effective temperature of star or flare taken as a typical blackbody tempera-

Table 1. Parameters of flares and QPPs.

QPP	Star	Date yymmdd	$P_{\rm QPP}$ s	$\Delta t_{\rm fl}$ s	$A_{\rm QPP}$	$A_{\rm fl}$	$\Delta m_{\rm U}$ mag	$W_{\rm t}$ s	$E_{\rm fl}$ 10^{33} erg
1	UV Ceti	081228	70 ± 19 107 ± 18	1817:	0.1	14.4	3.0	4210	0.17
2	UV Ceti	090101	24 ± 7	262	0.08	1.46	1.0	92	0.0037
3	Wolf 359	090128	46 ± 20	260	0.1	6.17	2.1	317	0.015
4	EV Lac	090719	19 ± 4	440:	0.07	1.47	1.0	119	0.25
5	EV Lac	090719	26 ± 5	255:	0.03	1.47	1.0	101	0.22
6	EV Lac	090719	26 ± 6	1200:	0.13	7.72	2.4	1326	2.8
7	EV Lac	090721	10 ± 3	300:	0.04	0.391	0.4	24.7	0.053
8	EV Lac	090721	14 ± 2 24 ± 2	135:	0.02	0.391	0.4	22.0	0.047
9	Wolf 424	100610	13 ± 3 57 ± 17	320	0.07	1.75	1.1	120	0.016
10	Wolf 424	100610	15 ± 3	459:	0.07	3.85	1.7	76	0.010
11	EV Lac	100708	49 ± 7	910:	0.03	0.248	0.2	69	0.15
12	EV Lac	100708	87 ± 18						
13	EV Lac	100708	$5.8^{+0.9}_{-1.2}$	340:	0.03	0.426	0.4	30.2	0.064
14	EV Lac	100708	18 ± 7 36 ± 5	550:	0.035	0.561	0.5	66	0.14

Notes. $E_{\rm fl}$ is evaluated using the following stellar effective temperatures and quiescent bolometric luminosities: 2728 ± 60 K and $(1.25 \pm 0.05) \times 10^{-3}\,L_\odot$ for UV Ceti, 2800 ± 50 K and $(1.11 \pm 0.02) \times 10^{-3}\,L_\odot$ for Wolf 359, 3270 ± 80 K and $(1.28 \pm 0.03) \times 10^{-2}\,L_\odot$ for EV Lac and 3013 K (2555/3800 K) and $1.59 \times 10^{-3}\,L_\odot$ for Wolf 424.

ture of 9000 K for a flare continuum) transmitted by the U filter, and $\eta = 0.63$ the fraction of the total flare-radiated energy in the optical continuum. With these we get the flares energies $E_{\rm fl}$ in the interval (0.0037–2.8) $\times 10^{33}$ erg.

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