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Photometric variability in FU Ori and Z CMa as observed by *MOST*[★]

Michal Siwak,[1][†] Slavek M. Rucinski,[2] Jaymie M. Matthews,[3] Rainer Kuschnig,[3,4] David B. Guenther,[5] Anthony F. J. Moffat,[6] Jason F. Rowe,[7] Dimitar Sasselov[8] and Werner W. Weiss[4]

[1] *Mount Suhora Astronomical Observatory, Cracov Pedagogical University, ul. Podchorazych 2, 30-084 Krakow, Poland*
[2] *Deparntment of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, Ontario M5S 3H4, Canada*
[3] *Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada*
[4] *Institut für Astronomie, Universität Wien, Türkenschanzstrasse 17, A-1180 Wien, Austria*
[5] *Institute for Computational Astrophysics, Department of Astronomy and Physics, Saint Mary's University, Halifax, NS B3H 3C3, Canada*
[6] *Départment de Physique, Université de Montréal, C.P. 6128, succursale: Centre-ville, Montréal, QC H3C 3J7, Canada*
[7] *NASA Ames Research Center, Moffett Field, CA 94035, USA*
[8] *Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

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ABSTRACT

Photometric observations obtained by the *MOST* satellite were used to characterize optical small-scale variability of the young stars FU Ori and Z CMa. Wavelet analysis for FU Ori reveals the possible existence of several 2–9 d quasi-periodic features occurring nearly simultaneously; they may be interpreted as plasma parcels or other localized disc heterogeneities revolving at different Keplerian radii in the accretion disc. Their periods may shorten slowly which may be due to spiralling in of individual parcels towards the inner disc radius, estimated at 4.8 ± 0.2 $R_\odot$. Analysis of additional multicolour data confirms the previously obtained relation between variations in the $B - V$ colour index and the V magnitude. In contrast to the FU Ori results, the oscillation spectrum of Z CMa does not reveal any periodicities with the wavelet spectrum possibly dominated by outburst of the Herbig Be component.

Key words: accretion, accretion discs – stars: individual: FU Ori – stars: individual: Z CMa.

1 INTRODUCTION

This paper presents results obtained for two well-known young stars, FU Ori and Z CMa, as a continuation of the *MOST* satellite photometric variability studies of young stellar objects.

FU Ori is an object of special interest which has been known since 1937, when in a time-scale of one year its brightness rose from 16 to 9.5 mag (in the photographic blue-band system) and then started to decay slowly at the rate of 0.015 mag yr^{-1} (Wachmann 1939; Kenyon et al. 2000). This outburst, and two similar events observed in the early 1970s in V1057 Cyg and V1515 Cyg, led to the creation of a class of eruptive young stars – 'FUor' stars (Herbig 1977) – currently consisting of about 20 members (Semkov & Peneva 2010, 2012; Miller et al. 2011). The pre-outburst spectra of FUors obtained for two members of the class, V1057 Cyg and V2493 Cyg (HBC 722), revealed that the progenitors were classical T Tauri-type stars (CTTSs).

An enhanced accretion in the disc at a rate of about 10^{-4} $M_\odot$ yr^{-1}, resulting in a major increase of the disc surface brightness and dominating over the stellar flux, was proposed as the source of the FUor outbursts (Hartmann & Kenyon 1985, 1996). Discovery of companions to FU Ori, Z CMa and other FUors (Reipurth & Aspin 2004; Wang et al. 2004), has initiated discussion whether FUor outbursts may be triggered by perturbations in the accretion discs at close periastron passage (Bonnell & Bastien 1992; Reipurth & Aspin 2004).

During an outburst of an FUor, emission lines, which are typical for CTTSs, almost completely disappear while the visual spectrum is dominated by absorption features produced in an inner accretion disc radiating as a stellar atmosphere of an F-G supergiant star. The outer, colder parts of the FUor discs produce a K–M type supergiant spectrum observable in the infrared (Kenyon, Hartmann & Hewett 1988). In accordance with the location of the brightest parts of the Keplerian disc seen in different wavelengths, the absorption line broadening diminishes from the visual to the near- and mid-infrared spectral regions, as observed for FU Ori by Kenyon & Hartmann (1989), Hartmann, Hinkle & Calvet (2004) and Zhu et al. (2009).

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[†] E-mail: siwak@nac.oa.uj.edu.pl

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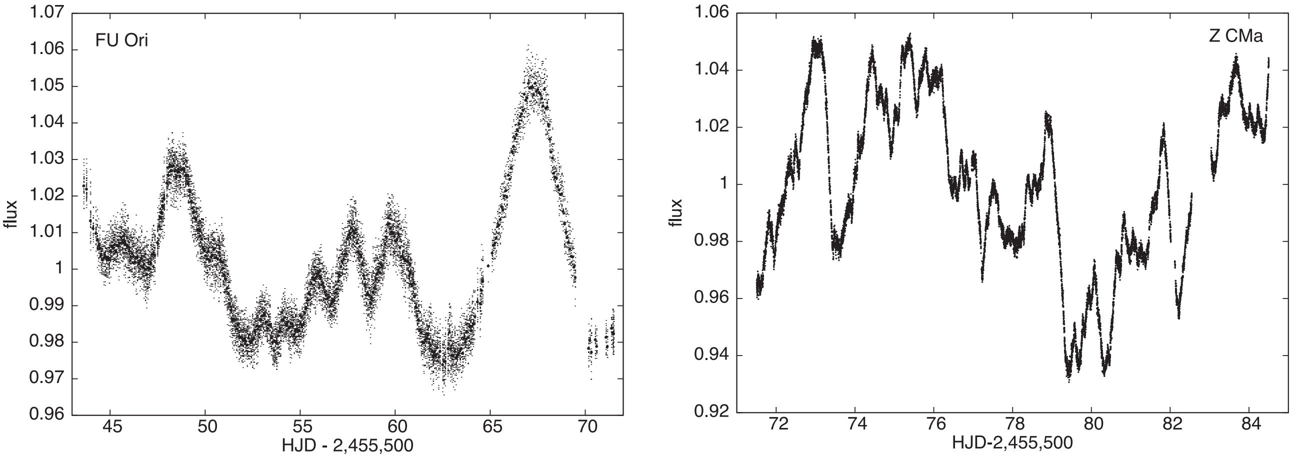

Figure 1. *MOST* light curves of FU Ori (all data points plus 362 *mean-orbital* averages, left-hand panel) and Z CMa (all 15 404 data points, right-hand panel) in normalized flux units.

Z CMa was recognized as a young star by Herbig (1960). The discovery, using infrared speckle interferometry, that the star is a very close 0.1 arcsec visual binary (Koresko et al. 1991; Hass et al. 1993) resolved the initial difficulties in interpretation of the complex spectral properties of the star (Covino et al. 1984). Spectropolarimetric observations revealed that it is the Herbig Be component of the binary which dominates the infrared continuum and total luminosity of the system. The same star is apparently the source of the emission lines polarized in the dusty disc envelope and observed in visual part of the spectrum (Whitney et al. 1993). The Herbig Be star is also responsible for $\Delta V = 1$–3 mag outbursts (van den Ancker et al. 2004; Grankin & Artemenko 2009), caused by variable scattering geometry (Szeifert et al. 2010), periods of strong mass-loss from the disc (Benisty et al. 2010) or the EXor outburst (Whelan et al. 2010). These outbursts are superimposed on the slowly decaying light curve of the visually brighter FUor star. This component contributes a typical – for FUors – rotationally broadened absorption spectrum produced in the accretion disc (Welty et al. 1992); it supplied about 80 per cent of the observed unpolarized flux at visual wavelengths (Whitney et al. 1993) when the system brightness was $V = 9.7$ mag.

Kenyon et al. (2000) argued that similarly to cataclysmic variables, accretion discs of FUors should produce flickering variability as a characteristic signature observable at visual wavelengths. By comparing a limited amount of ground-based data to the Monte Carlo synthetic variability model the authors suggested the possibility of $\sim$1 d quasi-periodicities with a V-band amplitude of about 0.035 mag, which would originate in the inner edge of the FU Ori disc. Motivated by these results and by the lack of similar studies for Z CMa, we decided to re-examine this issue by means of continuous, high-precision, space-based photometric observations. Additionally, to obtain information on the *wavelength–amplitude* dependence of the flickering, we observed FU Ori simultaneously by means of a ground-based telescope using intermediate-width Strömgren v and b filters. We describe details of these observations in Section 2. The methods used for light curve analysis and the results obtained for our targets are presented in Section 3 and then summarized in Section 4.

2 OBSERVATIONS AND DATA REDUCTIONS

The optical system of the *MOST* satellite consists of a Rumak-Maksutov *f*/6, 15 cm reflecting telescope. The custom broad-band filter covers the spectral range of 380–700 nm with the effective wavelength falling close to the Johnson V band. The pre-launch characteristics of the mission are described by Walker et al. (2003) and the initial post-launch performance by Matthews et al. (2004).

The stars investigated in this paper were observed in the direct-imaging mode of the satellite. FU Ori was observed nearly continuously for 28 d between 2010 December 13 and 2011 January 9, during 362 satellite orbits. The individual exposures were 30 s during the first part of the run and 60 s during the last 10 d of the run. Immediately after the FU Ori observations, on 2011 January 10 *MOST* started a 13 d long monitoring of Z CMa, which was observed with 60 s exposures. Some occasional interruptions in data acquisition, visible in the light curves (Fig. 1) did not impact the scientific results.

The *dark* and *flat* calibration frames for the *MOST* data were obtained by averaging a dozen *empty-field* images specifically taken during each observing run, or – for the case of the 30 s long exposures of FU Ori – from frames with the target localized far beyond its optimal position due to occasional satellite guiding errors. Aperture photometry of the stars was obtained from the *dark* and *flat* corrected images by means of the DAOPHOT II package (Stetson 1987). As in our previous investigations, a weak correlation between the star flux and the sky background level within each *MOST* orbit was noted and removed; it was most probably caused by a small photometric non-linearity in the electronic system (see Siwak et al. 2010). As a result, we obtained very good quality light curves, particularly for Z CMa (see Fig. 1). In the analysis we used the satellite–orbit (101 min) averages for FU Ori whose median error was 0.0036 of the mean normalized flux. We note that FU Ori is surrounded by a bright nebula which slightly decreased the photometric accuracy of the data. For the brighter Z CMa, the data were binned into smaller, 14.5 min bins consisting of typically 10–15 observations with the median error 0.0011 per bin. The finer binning was done in order to preserve information on the short time-scale variability of the star.

During four nights of 2011 January 4, 5, 8 and 9, we simultaneously observed FU Ori in v and b Strömgren filters using the 60 cm telescope at the Mount Suhora Observatory, Cracow Pedagogical University. We were unable to obtain similar data for Z CMa due to poor weather conditions. The data were reduced in a standard way in the ESO-MIDAS software environment. Aperture photometry was obtained with the DAOPHOT II package. The photometry of FU Ori was done differentially utilizing a *mean comparison star* made of the three nearby, somewhat fainter stars having colour

Table 1. Basic information on FU Ori and the comparison stars used for differential photometry.

Star	V	$B-V$
FU Ori	9.74*	1.279(47)
GSC 00714−0203	10.555(88)	1.069(85)
GSC 00715−0188	10.682(93)	1.646(241)
GSC 00715−0123	11.337(119)	0.960(194)

*The average V magnitude of FU Ori during *MOST* observations as obtained from observations made by Grankin (private communication), Bruno Alain and Timar Andras (AAVSO).

indices similar to FU Ori (Table 1). Thanks to the proximity of the stars and similarity of the colours, corrections for differential and colour extinction were unnecessary.

3 RESULTS OF THE LIGHT-CURVE ANALYSIS

We performed analysis of the *MOST* data in a similar way to Rucinski et al. (2008, 2010) and Siwak et al. (2011), i.e. the Fourier analysis was done by simple least-squares fits of expressions of the form $l(f) = c_0(f) + c_1(f)\cos[2\pi(t - t_0)f] + c_2(f)\sin[2\pi(t - t_0)f]$ for an appropriate range of frequencies f, with the step of $\Delta f = 0.01$. The amplitude $a(f)$ for each frequency was evaluated as the modulus of the periodic component, $a(f) = \sqrt{c_1^2(f) + c_2^2(f)}$. The bootstrap sampling technique permitted evaluation of mean standard errors of the amplitudes from the spread of the coefficients a_i. This technique, for a uniform temporal sampling – as in our case – may give too pessimistic estimates of errors, but consistently we prefer this conservative approach.

For the Fourier analysis of the FU Ori variability, we used 362 *mean-orbital* data points, while in the case of Z CMa, which is much brighter, all 15 404 measurements, obtained every 60 s were used. For the wavelet analysis of Z CMa, the data have been averaged and partly interpolated into 1291 points on an equal-spacing grid at 0.010 067 d (14.5 min) steps. Similar interpolation for FU Ori, which suffered more interruptions, led to mapping into a grid of 395 points. The Morlet-6 wavelet provided the best match between the time-integrated power spectrum and original frequency spectrum of both FU Ori and Z CMa. This was noticed by Rucinski et al. (2008) and encountered later by Rucinski et al. (2010) and Siwak et al. (2011). The Morlet transforms of other orders result in systematic differences in the period scale.

3.1 FU Ori

3.1.1 Analysis of the Fourier and the wavelet spectrum

The upper envelope of peak amplitudes in the Fourier transform of the FU Ori data (Fig. 2, left-hand panel) appears to scale as flicker noise, $\propto 1/\sqrt{f}$, where f is the frequency. The first most prominent maximum at $f = 0.107$ cycles d^{-1} is visible as the largest and most intense feature in the wavelet spectrum (Fig. 3, left-hand panel) and directly in the light curve. Its period shortens gently from ∼9 to ∼8 d, somewhat similarly to the case of TW Hya (Rucinski et al. 2008; Siwak et al. 2011). However, we note that this periodicity is based on only three cycles so that its reality may be questioned. To test the validity of our results, we conducted tests on recovery of drifting, quasi-periodic features which additionally change their amplitudes. In each case we obtained very satisfactory reproduction of synthesized light curves, including the rates of period and amplitude changes.

Following our interpretation of TW Hya, we assume that the oscillation feature is produced by plasma condensations and/or other accretion disc heterogeneities, in turn produced by interactions of stellar magnetic field with the inner disc plasma, although we have no clear picture what causes these instabilities. If this is a correct view, then the period variations reflect a change in localization within the disc at radii (estimated from Keplerian periods) from about 12.2 to 11.3 $\mathrm{R}_\odot$, assuming a central star mass of 0.3 $\mathrm{M}_\odot$ (Zhu et al. 2007). The low inclination of the accretion disc of 55 deg (Malbet et al. 2005) should indeed permit to observe such inner disc structural changes.

Other peaks in the Fourier spectrum (Fig. 2) localized at $f = 0.166$, 0.215 and 0.263 cycles d^{-1}, (P = 6.0, 4.7 and 3.8 d, respectively) are represented by the much fainter and apparently constant features visible in different parts of the wavelet spectrum. They cannot be well characterized and may actually represent processing artefacts for the relatively short data set or a pure random flickering. We note that these three periodicities are not directly visible in the FU Ori light curve.

In addition to the features described above, the light curve contains a well-defined directly visible short-periodic signal at

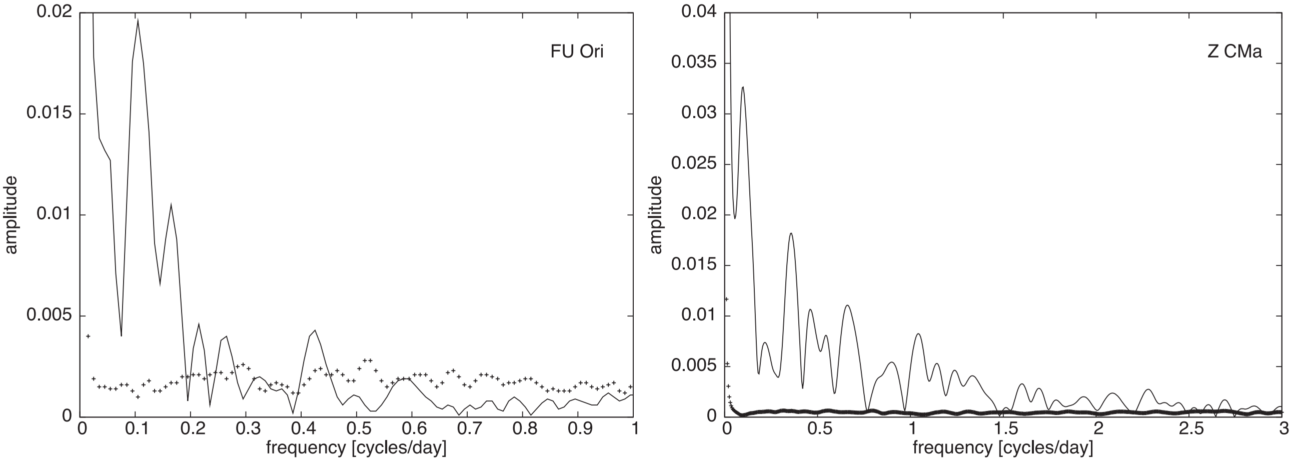

Figure 2. Fourier analysis of the variability data computed from the *mean-orbital* data points of FU Ori (left-hand panel) and from all data points of Z CMa (right-hand panel). The amplitude errors estimated through bootstrap repeated sampling are represented by small points.

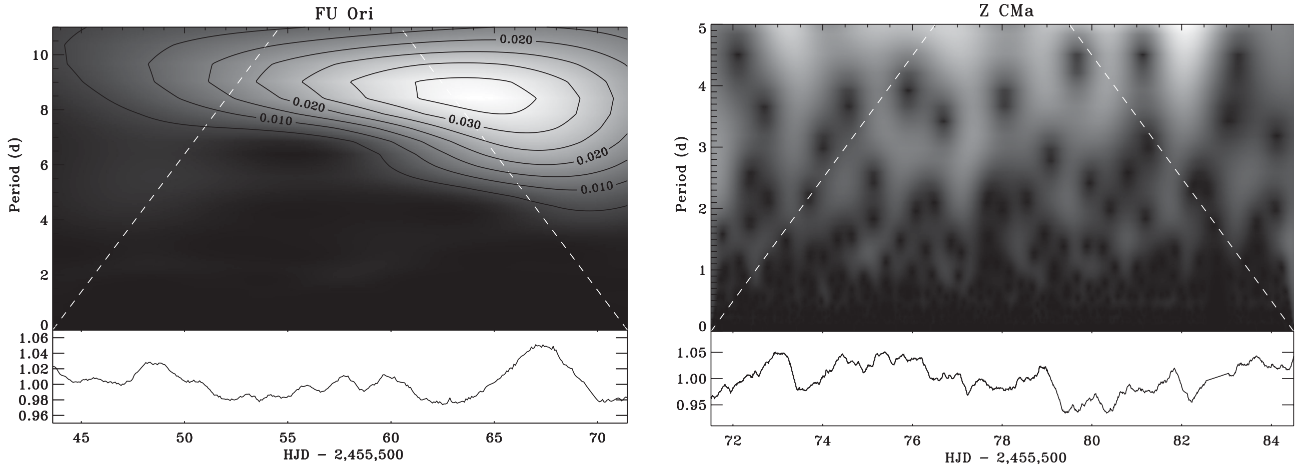

Figure 3. Morlet-6 wavelet spectra of FU Ori (left-hand panel) and Z CMa (right-hand panel) calculated for the whole accessible period range upto 11 and 5 d, respectively. The light curve in normalized flux units is shown at the bottom of the panels. Ranges not affected by edge effects in the wavelet transformation are located between the two white broken lines.

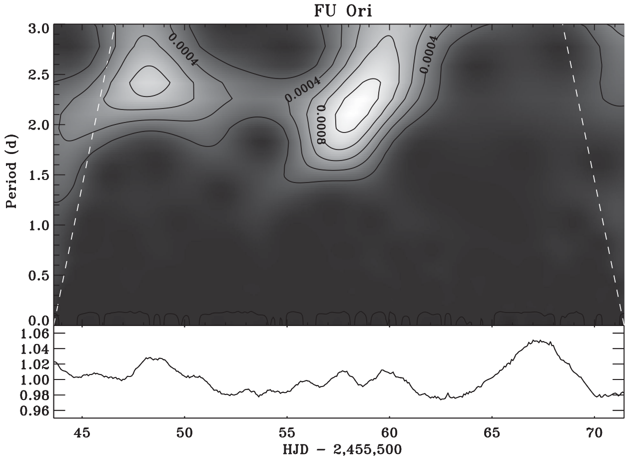

Figure 4. The upper panel shows the wavelet spectrum of FU Ori (as in Fig. 3), but limited to 3 d to improve visibility of shorter oscillations. The light curve in normalized flux units is shown at the bottom of the panel. Ranges not affected by edge effects in the wavelet transformation are located between the two white broken lines.

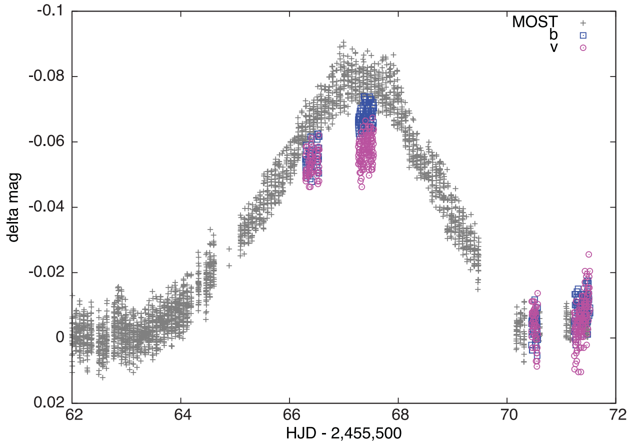

Figure 5. A fragment of FU Ori light curve covered by the ground-based data. The light curves from *MOST* (small crosses) and in b and v filters (squares and circles) were shifted to the same level at the light minimum for an easier comparison.

$f = 0.424$ cycles d^{-1}, which disappears after HJD ≈245 5560. To improve its visibility we prepared a second wavelet image (Fig. 4), which reveals one apparently drifting feature with two well-defined peaks: the first one is localized at $P = 2.4$ d and the second at $P = 2.2$ d. Within the model of orbiting plasma in the inner disc, this would correspond to the Keplerian radii within 5.1–4.8 $R_{\odot}$. We do not see any obvious short-period signals at periods shorter than $P = 2.2$ d which may indicate that the inner accretion disc is truncated at about 4.8 $R_{\odot}$. This value is in agreement with the inner disc radius of $5.5^{+2.9}_{-1.8}\,R_{\odot}$ obtained from interferometric observations by Malbet et al. (2005), but is three times smaller from that obtained by Eisner & Hillenbrand (2011) – 15 ± 4 $R_{\odot}$.

3.1.2 Analysis of multicolour observations

Although the weather conditions during the ground-based observations were poor, we were very fortunate to have the four clear nights exactly when the star showed both the maximum and the minimum of its 8 d long oscillation (Fig. 5). This enabled us to address the *wavelength–amplitude* dependence in the b (4670 Å) and v (4110 Å) filters of the Strömgren photometry.

As discussed by Kenyon et al. (2000), the observed variability amplitudes decrease at shorter wavelengths. In order to compare our results with the relation of the changes $\Delta(B - V)$ and ΔV found by Kenyon et al. (2000), we used the average magnitudes in our two filters and found the mean colour index $\Delta(0.5 \times [v + b]) - \Delta V = 0.016 \pm 0.002$ mag. It is larger by 0.06 mag than that returned by equation 6 of the Kenyon et al. (2000), but agrees with their finding that the $B - V$ colour index becomes redder as the star becomes brighter. This relation allowed the authors to constrain the effective spectrum producing the flickering to F7–G3 spectral type.

The 0.06 mag difference in the colour index can be explained by the difference in the location of the dominant source of the observed stellar flux. The respective annuli in the disc, at different Keplerian distances, should produce different *wavelength–amplitude* relations. The 9–8 d oscillation feature is assumed to be produced at the distance of 12−11 $R_{\odot}$, where according to FU Ori disc models (Zhu et al. 2007) $T_{\rm eff} \approx 5000$ K. Obviously, the amplitudes of flux variations arising at such a large distance are considerably reduced by the dominant flux produced in the innermost disc. As the feature approaches the central star on a spiral orbit, it moves to warmer disc annuli. As a consequence, the wide-band *MOST* filter receives initially a small fraction of the energy emitted at 12 $R_\odot$, but then this fraction increases as the spiralling-in process continues.

Changes in the amplitude of the 9–8 d periodic feature may be questioned in view of the duration of the whole *MOST* observations lasting for four weeks. However, the general trend of the progressively growing amplitude as the period shortens seems to be visible both directly in the light curve (Fig. 1, left-hand panel) and in the wavelet spectrum (Fig. 3, left-hand panel). The amplitude reached about 0.03 mag in the first and the second cycle (the overlapping non-sinusoidal oscillations do not allow for a more accurate estimate) and 0.075 mag in the third. Once again we stress that this finding bases on three oscillations only. However, our data do reveal a similar effect, of the amplitude growing up from 0.005 to 0.02 mag, also for the $P = 2.4{-}2.2$ d feature; such a drift would correspond to a motion from 5.1 to 4.8 $R_\odot$, where the disc annuli have temperatures $T_{\rm eff} \approx 6400$ K (Zhu et al. 2007). The difference in the amplitudes with Kenyon et al. (2000) may have resulted from averaging of independent wave trains during their observations or may reflect a real, physical difference in sizes of the gas elements.

3.2 Z CMa

As mentioned in Section 1, about 80 per cent of the unpolarized visual flux of Z CMa is produced by the FUor component. The direct flux from the Herbig Be star is obscured by a dusty envelope and visible as scattered continuum light, which is polarized at about 6 per cent and as emission lines (Whitney et al. 1993). The *MOST* satellite does not have any polarization capabilities and measures the total flux. The observations in 2011 January were obtained during the light maximum of a new outburst when, according to the AAVSO data base, the average total system brightness was $V = 8.7$ mag. This may explain the chaotic shape of the wavelet transform (Fig. 3, right-hand panel) containing many incoherent variations down to time-scales of about 0.3 d. At least a part of these oscillations may have their origin in the night-to-night and hour-to-hour variations of Hα, Hβ, Na I D P Cygni absorptions and in the Hβ emission peak (Chochol et al. 1998). Also, from speckle observations obtained in the infrared *H*&*K* filters Hass et al. (1993) reported that both components of the close visual double were varying independently by ~0.5 mag.

The time variability spectrum of Z CMa is somewhat similar to that of the Herbig Ae star HD 37806 (Rucinski et al. 2010). The chaotic variability at all time-scales and lack of any regularity in the Fourier or wavelet transforms strongly suggest that the time variability spectrum is dominated by the Be component which contributes at least 20 per cent to the total flux. Lack of any firm results is compounded by the relatively short duration of the observation run which lasted only 13 d. Unfortunately, the *MOST* observations of Z CMa done one year earlier, in 2010, obtained in a time of relatively moderate light variations were of a very poor quality due to technical problems.

4 SUMMARY

Continuous *MOST* satellite observations of FU Ori and Z CMa confirmed the presence of intensive, rapid (time-scales of single days) variations of their light which may have general characteristics of the flicker noise with amplitudes scaling as: $a \propto 1/\sqrt{f}$, similar to the CTTS TW Hya (Rucinski et al. 2008; Siwak et al. 2011). For FU Ori, the Fourier and wavelet transform spectra show quasi-periodic features, one well defined and possibly changing its period within 9–8 d and one much fainter at about 2.4 d, drifting down to 2.2 d. But we note an absence of any one-day periodicity in our data, contrary to the Kenyon et al. (2000) results which were obtained from a limited amount of unequally spaced, poor-quality data. We tentatively interpret these quasi-periodic variations as produced by hot plasma condensations and/or disc heterogeneities which develop in the magnetorotationally unstable inner parts at the Keplerian distances of about 12 and 5 $R_\odot$. The period variability may be interpreted as a spiralling-in or inward drift in the innermost disc. The shortest observed period of 2.2 ± 0.1 d may define the inner edge of the accretion disc at 4.8 ± 0.2 $R_\odot$, which agrees with the estimate of Malbet et al. (2005) from the interferometric observations. Within the *disc-locking* mechanism picture of the accretion processes, the rotational period of the star would be then close to 2 d. Although this was the interpretation of such oscillatory features for TW Hya (Rucinski et al. 2008; Siwak et al. 2011), Herbst (private communication) argued that for the case of TW Hya, hot condensation in the disc could not easily produce up to 20 per cent flux variations observed in the visual spectrum which is dominated by the central star. This is indeed a valid point, but we note that for the case of FU Ori the accretion disc luminosity overwhelms that of the central star by about 100 times.

Two colour Strömgren v and b ground-based observations of FU Ori confirmed the $\Delta(B-V)$ versus ΔV relation obtained by Kenyon et al. (2000). However, we obtained a slightly redder colour index of the dominant variations, what may be due to a more outward hotspot location (causing the 8 d periodicity) during our observations. This would agree with the interpretation of the *wavelength–amplitude* relationship through different locations of the dominant variable flux, with longer periods produced by more external and cooler parts of the accretion disc. In general, this effect may manifest itself within the wide-band *MOST* light curve and in the wavelet transform of the star variability as the amplitudes of the two drifting, oscillatory features markedly increased as their periods decreased. Future simultaneous *MOST* and ground-based, multiband observations conducted over a few months may help in investigation of the *wavelength–amplitude* relation for a range of possible periods. Such observations should be supported by spectral synthesis disc models, to localize the dominant light sources at various inner disc concentric annuli.

Z CMa, the complex binary consisting of an FUor and Herbig Be stars, was observed by *MOST* during 13 d close in time to the outburst maximum of the Herbig Be component. This led to the suppression of the FUor variability component and dominance of the very chaotic spectrum of oscillations of the Be component. The variability spectrum is somewhat similar to that of the Herbig Ae star HD 37806 (Rucinski et al. 2010). Future observations during quiescence level could help to disentangle the two light contributions.

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