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Optical and X-ray variability of the peculiar cataclysmic variable FS Aur with a magnetic and freely precessing white dwarf

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Abstract. We present preliminary results of long-term monitoring of the peculiar cataclysmic variable FS Aurigae conducted during the 2010-2011 observational season. The multicolor observations revealed, for the first time in photometric data, the precession period of the white dwarf, previously seen only spectroscopically. This is best seen in the $B-I$ color index and reflects the spectral energy distribution variability. Analysis of X-ray observations made with Chandra and Swift, also revealed the existence of both the orbital and precession periods in the light curve. We also show that the long-term variability of FS Aur and the character of its outburst activity may be caused by variations in the mass transfer rate from the secondary star as the result of eccentricity modulation of a close binary orbit induced by the presence of a third body on a circumbinary orbit.

Key words. binaries: close – novae, cataclysmic variables – X-rays: stars – stars: white dwarfs – stars: individual (FS Aurigae)

1. Introduction

FS Aurigae represents one of the most unusual cataclysmic variable (CV) to have ever been observed. The system is famous for a variety of uncommon and puzzling periodic photometric and spectroscopic variabilities which do not fit well into any of the established sub-classes of CVs.

The outlandish peculiarity of FS Aur is the existence of well-defined photometric optical modulations with the amplitude of up to ∼ 0.5 mag and a very coherent long photometric period (LPP) of 205.5 min that exceeds the spectroscopic orbital period (OP) of 85.7 min by 2.4 times (Neustroev 2002; Tovmassian et al. 2003). Such a disagreement in the photomet-

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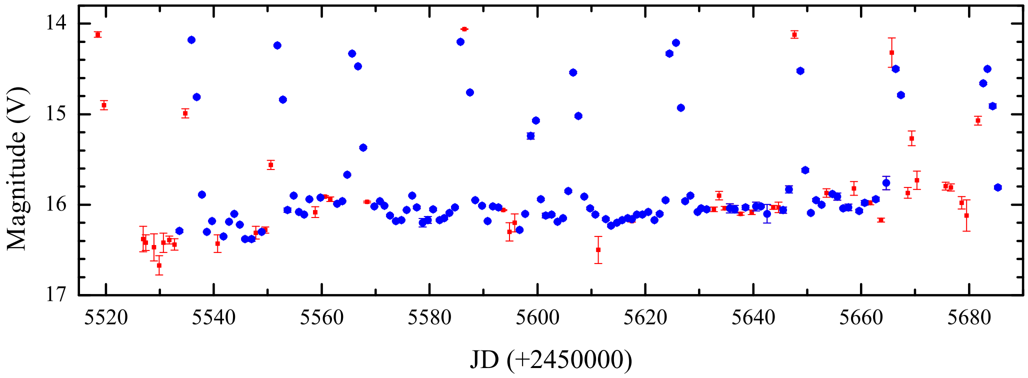

Fig. 1. Light curve of FS Aur, from the 2010-2011 observing campaign. Each point is the 1-day average of observations. Blue points represent the observations obtained by the authors, while the red squares represent the AAVSO observations.

ric and spectroscopic periods is highly unusual for a low mass binary system that is unambiguously identified as a CV.

During the spectral observations made in December 2004, Tovmassian et al. (2007) discovered a second long spectroscopic period (LSP) of 147 minutes, appearing in the far wings of the emission lines. They showed that frequency of this new period is equal exactly to the beat between the OP and LPP: $1/P_{beat} = 1/P_{orb} - 1/P_{phot}$.

Tovmassian et al. (2007) proposed that an interpretation of this puzzling behaviour of FS Aur might be a rapidly rotating magnetic WD precessing with the LSP. The spectroscopic period is a direct measure of rotation of the inner bright spot (precession period according to our hypothesis) and that the period seen in photometry (LPP) is the beat. According to existing models (Leins et al. 1992), the WD rotational period should be on the order of 50 - 100 sec in order to have the proposed precession period. Neustroev et al. (2005) and Tovmassian et al. (2010, 2012) intended to reveal the spin period of the WD by fast optical and X-ray photometry. They found a ~101 sec peak in both the power spectra, but it was not conclusive evidence.

Based on the short orbital period, FS Aur has been classified as a SU UMa star. Nevertheless, long-term monitoring of the system failed to detect any superoutburst/superhumps in its light curve. Instead, this monitoring revealed a very long photometric period of ~900 days. Tovmassian et al. (2010) showed that such a long period may be explained by the presence of sub-stellar third body on a circular orbit around the close binary.

In order to better understand the long-term variability and outburst activity of FS Aur, during the 2010-2011 observational season we have initiated and conducted an observing campaign, lasting more than 140 consecutive nights. Here we report preliminary results of these observations.

2. The 2010-2011 observing campaign

The observations were conducted every clear night from November 26, 2010 until May 3, 2011. The data were taken using telescopes with apertures of 0.28 to 0.5-meters, equipped with CCD cameras and standard Johnson V filters. Depending on the weather conditions, we monitored the star for 6–8 hours per night in the beginning of the campaign and for 3–4 hours at the end. Thus, more than 80 nights of time-resolved photometry were taken, and almost 14 000 V-band data points were obtained. In order to reduce the scatter from both ran-

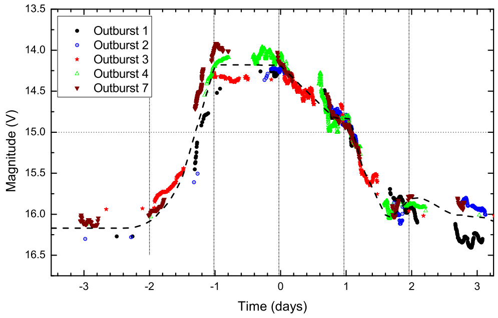

Fig. 2. The mean outburst profile of FS Aur is an average of 5 best covered outbursts.

dom errors and stochastic and short-term variability, we formed 1-day averages of these observations (Fig. 1).

Additionally, between nights of January 20 and March 9, 2011, 31 nights of time-resolved multicolor B, V, R_c, I_c photometry were taken. Moreover, after acceptance of our Swift ToO request, we obtained 5 more nights of multicolor observations, between March 28 and April 3, 2011.

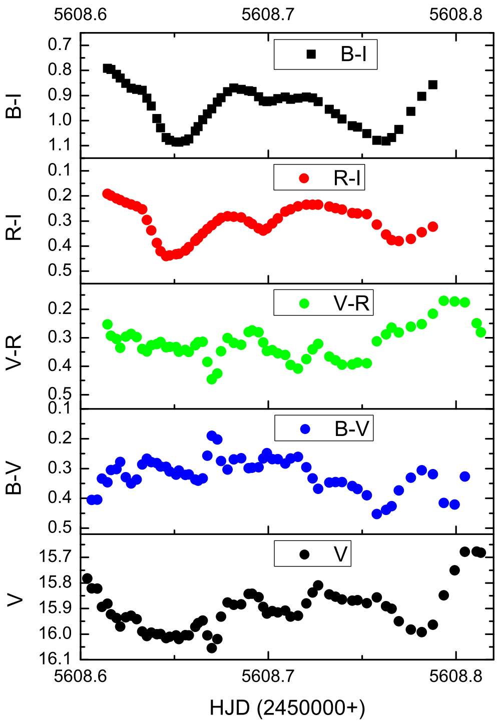

Fig. 3. A sample V light curve and color curves $B-V$, $V-R_c$, R_c-I_c and $B-I_c$ from JD 2 455 608.

3. Long-term variability and outburst activity of FS Aurigae

During the campaign, we succeeded in observing 11 consecutive outbursts, most of them in great details. Here we note the most prominent features seen in both the outbursts and quiescent light curves:

1. All the observed outbursts were of low amplitude ($\leq$ 2 mag) that is lower than most dwarf novae exhibit;
2. Nine of eleven outbursts had a very similar shape to the light curve: the fast rise (2.7 mag d^{-1}), a flat maximum, the relatively slow decline (0.8 mag d^{-1}), the rate of which, after the short plateau phase, dramatically increased to ~2.0 mag d^{-1}. The duration of each of these stages is around one day (Fig 2);
3. Two outbursts were of abnormally low amplitude and of short duration (around JD 2455600, Fig. 1);
4. The recurrence time of the normal outbursts was relatively short and stable, 18.1 ± 2.5 d;
5. During the decline stage of all the observed outbursts, large-amplitude modulations of 0.25–0.35 mag with a recurrence period of some 10 per cent longer than the OP ("superhumps") appeared in the light curve. They were observed for the most part of the quiescent stage but, approaching a next outburst, the superhumps usually disappeared to be replaced by the LPP modulations;
6. The system showed strong short-term variability during all stages of outbursts and quiescence;
7. During these observations, the average quiescent level increased 0.3 – 0.4 mag.

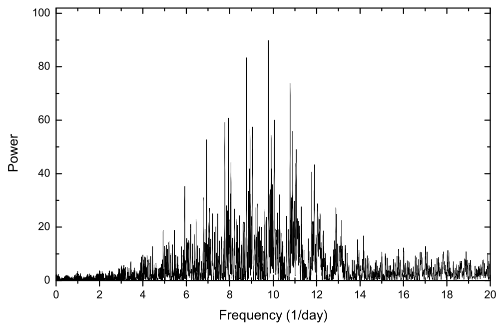

Fig. 4. The Lomb-Scargle power spectrum of the $B - I$ color-index curve of FS Aur. The strongest peak at $f = 9.776 \pm 0.003$ day^{-1} exactly coincides with the LSP which is the presumed precession period of the WD.

The strong variability during the quiescent state may be due to the variable mass transfer rate. The optical flux of a dwarf nova is dominated by the emission from an accretion disk particularly in the short period systems, while the emission from the disk is proportional to the mass-transfer rate. Schreiber et al. (2000) also found that the outburst behavior of a dwarf nova is strongly influenced by the variations of the mass-transfer rate. The latter is very sensitive to the Roche lobe size, which is proportional to the binary separation. In hierarchical triple systems, a third body can induce an eccentricity variation in an inner binary (Mazeh & Shaham 1979; Georgakarakos 2009). The long-term modulation is produced by the time-varying tidal force of the perturber upon the binary.

4. Optical and X-ray variability with the precession period

Usually, the most prominent features of the optical light curve of FS Aur is the well-defined LPP modulations of 205.5 min contaminated by strong stochastic variations, while the orbital variability is seen only occasionally (Tovmassian et al. 2003; Neustroev et al. 2005, 2012). However, during the presented observations the photometric behavior of FS Aur was even more complex than usually. In particular, during the most part of the quiescent stage, we observed modulations with a period of some 10 per cent longer than the OP.

This brightness variation was approximately the same in all filters. However, the color curves $B - V$, $V - R_c$ and $R_c - I_c$ also show a significant variation, more or less following the brightness variation: the color indexes $B - V$ and $R_c - I_c$ are generally anti-correlated and $V - R_c$ is correlated with the light curve (Fig. 3). The amplitudes of color variations are $\sim 0.05 - 0.1$ in all these colors.

Nevertheless, the behavior of the color index $B - I_c$ is significantly different. The most noticeable feature in $B - I_c$ is a modulation with a period near 0.1 day, even though it is sometimes contaminated or even completely replaced by the orbital/superhump variations. After visual inspection of the nightly $B - I_c$ curves, we selected a total of 16 nights (two-third of the observations taken in quiescence) when this variability is most evident. The Lomb-Scargle periodogram of the combined data (with the means, and linear trends subtracted for each night) is shown in Fig. 4.

The strongest peak at $f = 9.776 \pm 0.003$ day^{-1} exactly coincides with the beat period between the OP and LPP: $1/P_{beat} = 1/P_{orb} - 1/P_{phot}$, which is the presumed precession period of the WD in FS Aur. Variability with such a period was previously observed only in spectroscopic data as the Long Spectroscopic Period (Tovmassian et al. 2007).

During the PP, the properties of the X-ray and UV spectrum are expected to be even more variable because the accretion column on the WD magnetic pole is observed from different viewing angles.

Motivated by our findings, we performed a Swift ToO observation of FS Aur during 2011 March 29 – April 1 for a total of about 20.4 ksec. The object was also observed by Chandra in 2005 (25 ksec), and by Swift in 2007 (30 ksec). FS Aur is a relatively bright X-ray source with a count-rate of 0.38 cnts/s as observed with Chandra's ACIS-S3 CCD array. The important result of the X-ray observations is the detection of the modulations with the OP. Those X-ray modulations have a pulse profile and are stronger in the soft band (see Figs 3 and 4 in Tovmassian et al. 2012). We note that one

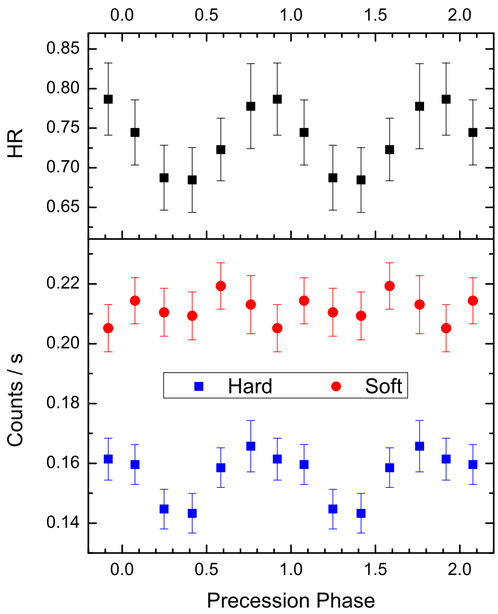

Fig. 5. The Chandra X-ray light curve and hardness ratio curve of FS Aurigae, folded with the precession period.

out of five pulses observed by Chandra, seems to be missing in the light curve.

In order to look for variability with the PP, we folded the X-ray data with the period of 147.3 min. There is a strong signature of modulation, mostly seen in the hard band (Fig. 4). What is remarkable is that the omission of one of the pulses in the Chandra X-ray light curve occurred around the time of the flux minimum during the precession period (Fig. 3 in Tovmassian et al. 2012).

5. Conclusion

Our new multicolor observations made during the 2010-2011 observational season revealed, for the first time in photometric data, the precession period of the WD, previously seen only spectroscopically. This is best seen in the $B-I$ color index and reflects the spectral energy distribution variability. Analysis of X-ray observations made with Chandra and Swift, also revealed the existence of both the orbital and precession periods.

Tovmassian et al. (2010) showed that a long ~900-d period observed in FS Aur may be explained by the presence of a sub-stellar third body on a circular orbit around the close binary. The long-term variability of FS Aur and the character of its outburst activity may also be triggered by variations in $\dot{M}$ from the secondary as the result of eccentricity modulation of a close binary orbit induced by the presence of a third body.

6. Discussion

ELENA PAVLENKO's Comment: One of the presented outbursts resembles so-called "failed outburst" observed in V1504 Cyg by Kepler (see Kato et al. 2011). You should check if after this event in FS Aur negative superhumps appeared.

VITALY NEUSTROEV: Thank you, we will check it out.

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