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Photometric activity of CQ Tau on the time interval of 125 years

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Abstract. The star CQ Tau belongs to the family of UX Ori type stars. It has very complex photometric behavior and complex structure of the circumstellar environment. In our paper we constructed the historical 125 years light curve of this star basing on the published photometric observations. It follows that besides a random component characteristic of UX Ori type stars, the large amplitude periodic component with the 10 year period is also present. Its existence was suspected earlier in [11]. New observations confirm its reality. It points to an existence of the second component close to the star. The density waves and matter flows caused by the companion motion lead to periodic changes in the circumstellar extinction and brightness of the star. This result is discussed in context of the recent observations of CQ Tau with high angular resolution.

1 Introduction

The star CQ Tau (Sp = F5 IVe, Mora et al. [1]) is one of the most active UX Ori type stars (UXORs). Its brightness varies with an amplitude up to $\Delta V \approx 3^m$. The star demonstrates all signatures typical for UXORs. Among them the so-called "blueing" effect is present consisting in the shift of the star color to the blue part of the spectrum in the deep brightness minima. This effect was firstly observed namely in CQ Tau (Gotz & Wenzel [2]), and its first interpretation was based on the assumption that this star was a binary and had a weak blue companion (Wenzel [3]). When the main component is screened by the circumstellar (CS) dust cloud the radiation of the blue companion begins to dominate. We will return to the idea of the CQ Tau binarity later, and now let us note that discovery of the same "blueing" effect in other UXORs closed the idea of binarity as a possible reason of this effect. The current explanation of this effect assumes that the blue radiation source of UXORs is the scattered radiation of the protoplanetary disks whose contribution increases during deep minima [4]. Observations of the high linear polarization in the deep minima confirmed this model (see [5] and cited papers therein). On the base of these observations it has been suggested that the CS disks of UXORs are inclined at a small angle to the line of sight, and this is the main reason of their specific variability.

This conclusion was generally supported with interferometric observations (see Kreplin et al. [6]) and cited papers therein). However, in the case of CQ Tau the situation was more complicated. Interferometry in the near infrared (IR) spectrum region revealed (Eisner et al. [7]), that the inclination angle of the inner region of the CS disk to the line of sight was equal to 48° that contradicted to the status of UXORs. Interferometric observations in the submillimeter range of the spectrum turned out to be even more surprising. They showed that the outer part of the disk is observed almost pole-on (Chapillon et al. [8], and this result was recently confirmed by observations with the ALMA interferometer (Ubeira-Gabellini et al. [9]).

No less complex is also the long-term brightness variability of the star (Minikulov et al. [10], Shakhovskoy et al. [11], Grinin et al. [12]). Using the data from these papers, we can trace the photometric activity of CQ Tau during about of 100 years. The first observations were fulfilled with the photographic method. They showed that the star was bright for a long time (about of 40 years), and its brightness fluctuated within 0.4-0.7m [12]. Around the middle of the last century the photometric activity of CQ Tau has changed dramatically: the star began to demonstrate deep brightness minima with an amplitude up to 2-3^m. The long lasting cycles began to be observed along with stochastic variability.

Periodogram analysis of the photometric series revealed two large periods: one with duration of about 20-21 years and another period was about half of the first one: $\approx$ 10 years [11]. After their removing a short 3 year period has been found.

Taking into account the large duration of the activity cycles, new observations are needed for their confirmation. The last observation of the CQ Tau, used in [11,12], was fulfilled in 2003. Twenty years passed since that time, and now a possibility appeared to prolong the brightness curve of the star. We consider below what does it give for study of the photometric activity of CQ Tau.

2 Historical light curve of CQ Tau

Figure 1 shows the light curve of the star in the B band plotted according to the data of [10-12]. It is completed with new observations from the ASAS-SN (All-Sky Automated Survey

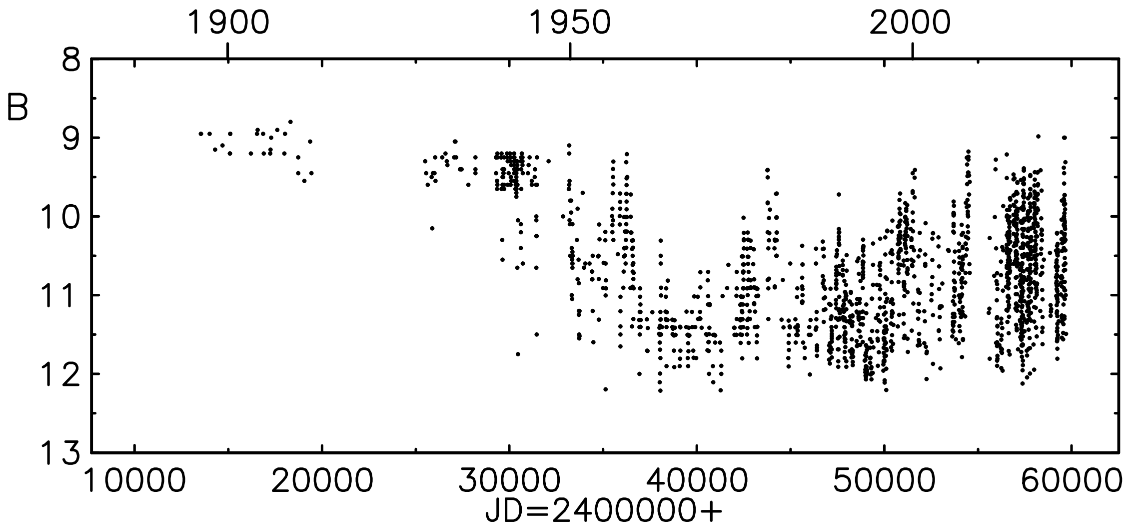

Рис. 1: Historical light curve of CQ Tau in the B-band according to the published data. The first observation has been done in Moscow in 1895.

for SuperNovae, Kochanek et al., [13]) and AAVSO (the American Association of Variable Star Observers: https://www.aavso.org/) databases. When we plotted this light curve we used published observations fulfilled both by cited authors and by authors to whom they referenced in their papers. As it is known, observations presented in ASAS-SN as well as the most of observations in AAVSO were made in the V band. In order to transform them to the B band we used observations by Berdugin et al. [14] made in UBVRI bands. With their help we obtain a function connected magnitudes of CQ Tau in the B and V bands B = - 0.18V2 + 4.73V - 18.54. As it is shown in Appendix, this ratio ensured accuracy 5% for transition from V to B, that is quite enough for our purposes taking into account that changes in the brightness amplitude are 3 magnitudes.

It is directly seen from the CQ Tau light curve that the large cycle of the photometric activity with duration of 20-21 year is not traced in the new observations. On the contrary, the 10 year cycle is clearly seen. It is also confirmed by the periodogram analysis of the photometrically most active part of the star light curve (MJD $>$ 35000) shown in Fig. 2. One can see a presence of two periods: 10 years and 321.1 days. The latter is the year-linked to the 10-year period, it reflects the presence of the annual breaks in the observations. After subtracting the 10 year period we did not find the traces of the 3 year period obtained by Shakhovskoy et al. [11] in the remnant periodogram. Thus, the new periodogram analysis of the CQ Tau photometric activity confirmed a reality of only 10 year period. The convolution of the investigated part of the photometric series with the 10 year period is shown in Fig. 3.

From Fig. 3 it follows that the 10 year period is mainly revealed in the periodic modulation of the brightness at the bright state of the star and amplitudes of the minima. As it is seen from the light curve (Fig. 1), this modulation is observed on the systematic increase in the attenuation amplitude. Also the gradual brightening trend is distinctly seen.

3 Discussion and Conclusion

Presence of the 10-years period of the photometric activity in CQ Tau indicates to an existence of the companion in the vicinity of the star. Results of the interferometric observations of CQ Tau in the millimeter range testify the same (Tripathi et al. [15]; Wolfer et al. [16];

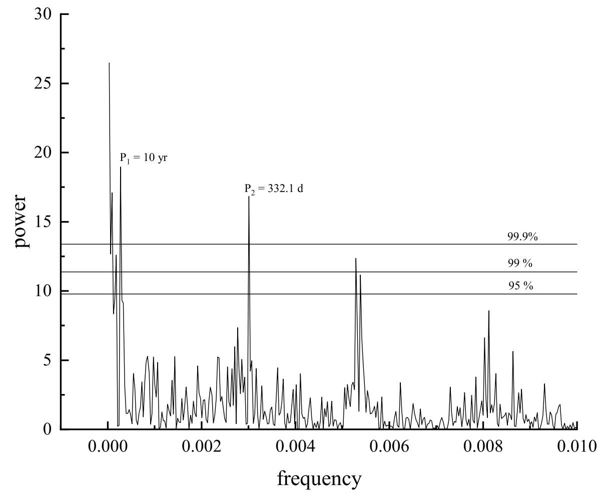

Рис. 2: The Lomb-Scargle periodogram of the most active part (JD > 35000) of the CQ Tau photometric series.

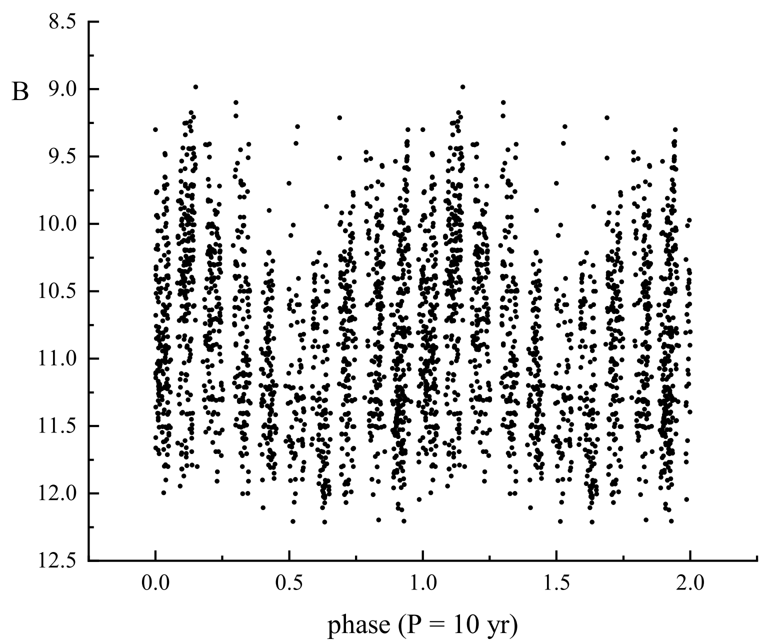

Рис. 3: The convolution of the CQ Tau observational photometric series with the 10 year period.

Ubeira-Gabellini et al. [9]). They showed that there is a vast cavity weakly filled with the matter in the central part of the protoplanetary disk of the star. Such cavities are formed in the young binary systems due to the tidal disturbances caused by the orbital motion of components (Artymowicz and Lubow [17]). Periodic perturbations lead to the formation of spiral density waves, and they are actually observed in images of the CQ Tau disk (Ubeira-Gabellini et al. [9], Uyama et al. [18], Hammond et al. [19], Safonov et al. [20]. However attempts to find a companion have not been successful so far [19].

According to Ubeira-Gabellini et al. [9], the cavity in the CQ Tau protoplanetary disk stretches from 15 to 25 AU. Numerical simulation performed by these authors showed that such a cavity can be formed by the planet with the mass of 6-9 M_{Jup} moving on the circular orbit with the radius of 20 AU. The orbital period of the planet with the mass of 1.67 $M_{\odot}$ will be equal to 69 years that obviously contradicts to the 10 year photometric period.

Is there a possibility to avoid this contradiction? We suppose that such a possibility exists if to drop an assumption about the circular orbit of the secondary and to increase its mass. According to models by Artymowicz and Lubow [17], in this case one can obtain the cavity of the same size with at a lower value of the large semi-axis of the orbit but respectively with a lower period. One should keep also in mind that according to the interferometric data in the near IR spectrum region (Eisner et al. [7]) the inner disk of CQ Tau is inclined relatively to the outer disk. This means that the orbit of the low mass companion can be also inclined relatively to the plane of the main disk. We intend to consider these questions in more details in the forthcoming paper. The main question also remains open: what happened in the environment of the star, which led to radical change in its photometric activity in the middle of the last century?

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4 Appendix

As mentioned above, the main part of photometric observations of CQ Tau from ASAS and AAVSO archives were fulfilled only in the V band. We determined relevant factors to transform the CQ Tau light curve from the V band to the B band, and used them for plotting the historical light curve. For this purpose we used the photometric observations of CQ Tau from the paper by Berdyugin et al. [13]. They are shown in Fig. 4. The dashed line shown in the same figure is defined by the second degree polynomial obtained when fitting to observations with the least square method. The dashed line in Fig. 4 sets a functional link between B and V values and described by the ratio: B = - 0.18 V^2 + 4.73V - 18.54. One can see that an accuracy of the V to B transition with the use of this ratio no worse than 0.05^m for most observations presented in Fig. 4.

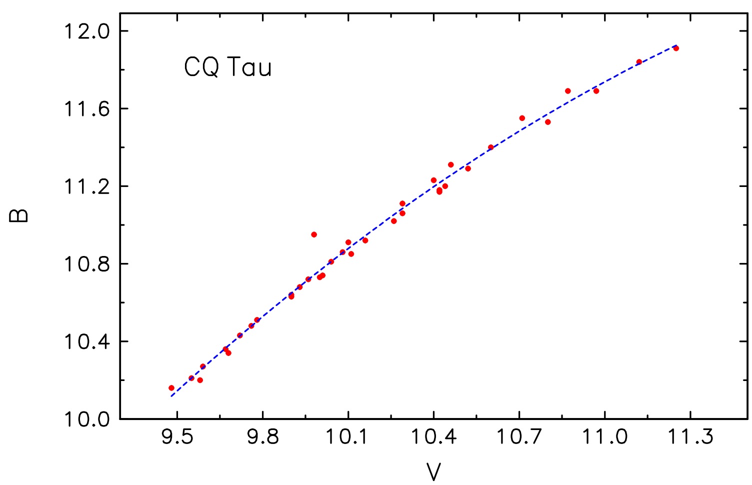

Рис. 4: CQ Tau stellar magnitudes in the B and V bands according to data by Berdyugin et al. [13].