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The Eclipsing Dwarf Nova EX Dra — A short review

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The review presents the results of a study of eclipsing dwarf nova EX Dra in various spectral regions, both observational and theoretical, based on the data from the literature. They include a description of the physical properties and parameters of the system. The results of a long-term photometric observations obtained earlier by the authors for this cataclysmic variable are briefly presented.

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1. Introduction

Dwarf novae are a subclass of the cataclysmic variables, consisting of a late-type main sequence star (secondary star) which fills its Roche lobe and transfers mass to a more massive white dwarf (primary star). The transferred material forms a disk being accreted onto the white dwarf surface [1].

Eclipsing cataclysmic variables are valuable because they provide the opportunity to study the radiative properties of accretion disks through analysis of the eclipse profiles. Generally, properties of the system are determined either through parameter-fitting models or through maximum-entropy eclipse mapping techniques [2].

Most such systems belong to the SU Uma class and they are found below period gap 2-3 h. Above the gap there are 6 eclipsing dwarf novae: EM Cyg, EX Dra, BD Pav, U Gem, GY Cnc and IP Peg, but only 3 of them are deeply eclipsed: EX Dra, GY Cnc and IP Peg.

EX Dra is of particular interest because of these three it has the longest P_{orb}, highest i (most deeply eclipsed) and the highest mass ratio $q = 0.75 \pm 0.10$.

2. A Brief History of EX Dra system

EX Dra (HS1804+6753) with $\alpha = 18^h04^m14.11^s$ and $\delta = +67°54'12.2''$ was detected in the Hamburger Quasar Survey [3].

A subsequent observations of Barwig et al. [4] showed: EX Dra — eclipsing dwarf nova with deep eclipses $\sim 1.5^m$ and $P_{orb} > 5^h$. Every 10-30 days this system undergoes outbursts that are up to 10 days in duration. The amplitude of an outburst is $\sim 2 - 3^m$. The brightness of EX Dra is $\sim 13.5^m$ during outburst and $\sim 15^m$ in quiescence. EX Dra orbital period was determined as 5.04^h by Fiedler [5], he also published eclipse timings.

Spectrum of the secondary M1V–M2V implies that the absolute magnitude of EX Dra lies in the range 8.8 < MV(2) < 9.7.

3. The Main Results of Spectroscopic Observations

Spectroscopic studies of the system which was provided by Billington et al. [6] indicated that H_α emission lines in its spectrum formed near the hot spot on the accretion disk and/or near the inner Lagrange point L_1. After correction for heating of the surface of the secondary with hot radiation of white dwarf the authors obtained the semi-amplitude of the secondary $K_2 = (210 \pm 10)$km/s. Taking into account the radial-velocity curve of white dwarf the mass ratio $q = M_1/M_2 \sim 1.25$ was found.

The following main parameters of EX Dra were derived from analysis of spectroscopic and photometric observations of Fiedler, Barvig & Mantel [5]: $M_1 = 0.75M_\odot$, $M_2 = 0.56M_\odot$, $i = 84.2°$.

Ritter & Kolb [7] in their Catalogue give the following parameters of EX Dra: $i = (85.8 \pm 0.06)°$, $M_{wd} = (0.78 \pm 0.02)M_\odot$, $M_{rd} = (0.59 \pm 0.02)M_\odot$.

Baptista, Catalan & Costa [8] analysed V and R light curves in quiescence and outburst. From their analysis of eclipse profiles using eclipse phases of the primary star and a bright spot, found values $q = 0.72$ and $i = 85°$. The main parameters of EX Dra was derived as $M_{wd} = (0.75 \pm$

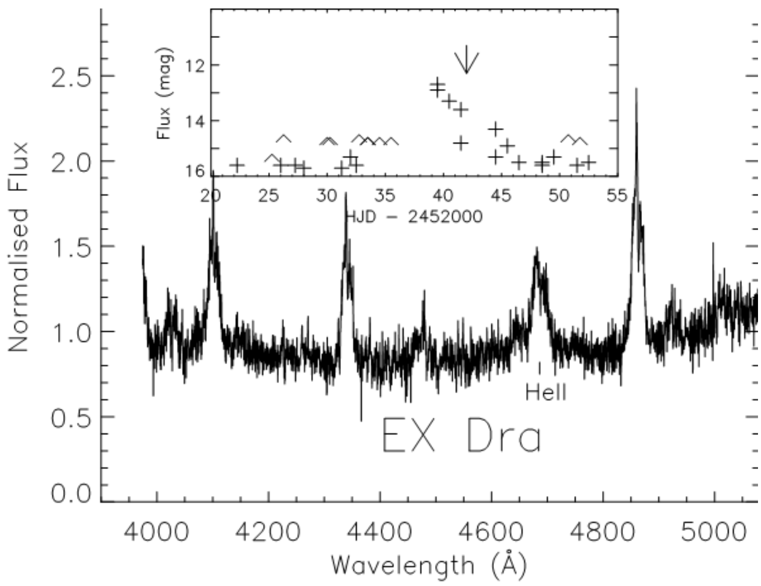

Figure 1: The spectrum of dwarf nova EX Dra during outburst from "Atlas of outburst spectra of dwarf novae" Morales-Rueda & Marsh (2002)

$0.15)M_\odot$, $M_{rd} = (0.54 \pm 0.10)M_\odot$, $i = (85 \pm 2.5)^\circ$ and the distance estimated as $d = (290 \pm 80)pc$. They also revised the linear ephemeris, fitted O–C residuals by a sinusoid with a period of 4 yr and an amplitude of 1.2 min.

Morales-Rueda & Marsh in 2002 [9] presented the "Atlas of outburst spectra of dwarf novae". In this Atlas the spectra of EX Dra during the outburst were first published. It is shown in Fig 1. There are strong helium lines HeII 4686 in emission in them.

Shafter & Holland [10] present *BVRI* eclipse light curves in quiescence. It is a first attempt to analysed multicolour light curves with a parameter-fitting model. The basic parameters of EX Dra were determined, — the width of the eclipse was used to put a lower limit on the orbital inclination $i > 83^\circ$ for $q < 0.81$. For the fixed temperature of the secondary $T_2 = (3750 \pm 150)^\circ$K (corresponding to the spectral type M0-2V), the best-fit temperature of the white dwarf (primary) is $T_1 = (50000 \pm 2000)^\circ$K, the temperature of the hot spot $T_{sp} = 40000^\circ$K and temperature of matter at the disk's outer edge is $T_d = (6500 \pm 1000)^\circ$K, the disk radius is $R_d\xi = (0.50 \pm 0.05)$ (where ξ is the distance between L_1 and the centre of mass of the white dwarf), parameter $\alpha_g = 0.3 \pm 0.2$. This parameter show the change of temperature along the radius of the accretion disk and depends on the viscosity of the matter in the disk. For a stationary disk it is 0.75 [11]. The distance to EX Dra was estimated as $d = (240 \pm 90)pc$ (different from Baptista estimation). Their revised ephemeris showed a cyclical variation with a period of 5 year.

The result of fitting of the observational eclipse profile of EX Dra obtained by Shafter & Holland [10] with model profile is shown in Fig.2. The binary parameters of EX Dra system obtained for three values of the orbital inclination q are given in Table 1.

Knigge [12] included EX Dra system in his comprehensive study of spectral types of donor stars in cataclysmic variables.

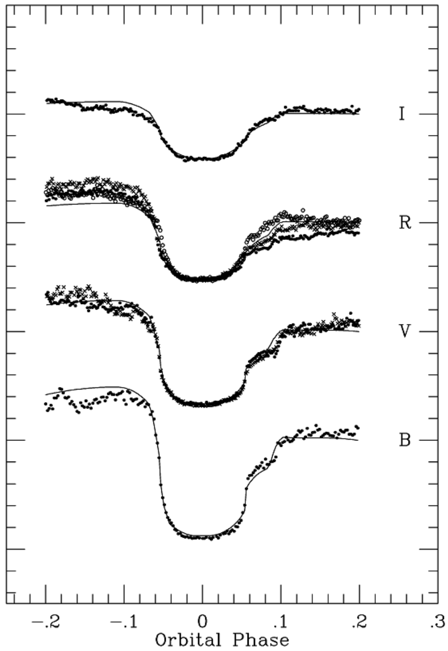

Figure 2: Fitting of observational eclipse profile with model profile (solid line) for value $q = 0.75$ as an example, Shafter & Holland, 2003

Table 1: Binary parameters of EX Dra from Shafter & Holland, 2003

Parameter	q=0.70	q=0.75	q=0.80
i (deg)	86.2	84.6	83.5
$a(R_o)$	1.61	1.59	1.58
$R_{L1}(a)$	0.54	0.53	0.52
$R_1(R_o)*$	1.07	1.13	1.17
$M_1(M_\odot)$	0.75	0.71	0.67
$R_2(R_o)*$	0.56	0.56	0.57
$M_2(M_\odot)$	0.53	0.53	0.53

4. The Main Results of Photometric Observations

Harlaftis et al. [13] performed observations in BVI filters during outburst. From analysis of their observations they conclude that accretion disk is asymmetric, the light curves show the existence of bright spot changing significantly from night to night, and a flickering exists on the light curve during the slow rise to the outburst.

Halevin & Henden [14]

Pilarchik, Wolf, Dubovsky et al. [15] measured photoelectrically 35 new eclipses as a part of long-term monitoring of this system. Using published (a total of 97) and new mid-eclipse times for the period 2004–2011 they constructed diagram, find period modulations with semi-amplitude of 2.5 min. The fractional period change is roughly $\Delta P/P = 3 \times 10^{-6}$. No confirmation of an existence of a five-year cyclic period of $O - C$ values declared by Baptista et al. [8] or a four-year cyclic period found by Shafter & Holland [10] has been found.

Court et al. [16] studied the eclipses during two outbursts by $TESS$ data. In both cases these data covered the beginning and the end of the outburst (with 1^d data gap caused by $TESS$ telemetering data back to the Earth). The eclipses undergo a hysteresis loop in eclipse – out-of-eclipse flux space; the direction in which the loops are executed strongly suggests an outburst that is triggered near the inner edge of the accretion disc and propagates outwards. So the outbursts in EX Dra system are "inside – out" outburst as it was predicted by hydrodynamic studies of dwarf nova accretion discs and confirmed in other systems by spectroscopic means (see Fig 3).

The direction of the loop executed in eclipse-depth/out-of-eclipse flux space could be used as an excellent test to phenomenologically distinguish between "inside out" and "outside in" outbursts in other eclipsing novae. The authors found a period of $0^d.2099385(6)$, slightly longer than previous periods of this object ($0^d.209936981$, Baptista et al. [8]). The $TESS$ light curves of EX Dra show evidence of a strong negative superhumps during quiescence with a period of $\sim 4.81^h$.

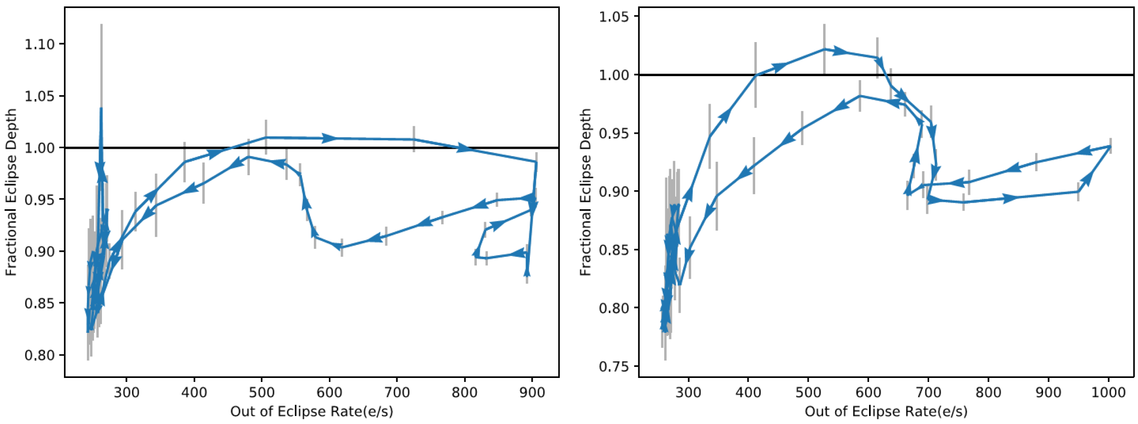

Figure 3: Plot of fractional eclipse depth against out-of-eclipse flux for the eclipse $TESS$ data. Arrows show the direction in which the hysteretic loops were executed over during the outburst.

5. The Results of High-Speed Photometry

Giannakis, Harlaftis & Papadimitriou in 2000 [17] performed B band photometry of EX Dra in quiescence and on the stage of outburst decline. During outburst they found periodicities with $\sim 115sec$ and $\sim 123sec$ which they interpreted as pulsations of accreting white dwarf in response to the enhanced mass transfer rate.

Baptista & Catalan [18] used eclipse mapping during early techniques to study the structure and time evolution of the accretion disc throughout the outburst cycle. The comparative analysis of light curves during early rise to outburst maximum with curves in quiescence show that a one-armed spiral structure develops in the accretion disc of EX Dra on the rise to maximum.

Joergens, Spruit & Rutten [19]. found evidence of spiral shocks in the accretion disc of EX Dra from Doppler tomography close to outburst maximum.

Thus, EX Dra is between 4 cataclysmic variables that have been seen to show hints of spiral structure in their discs [19–22].

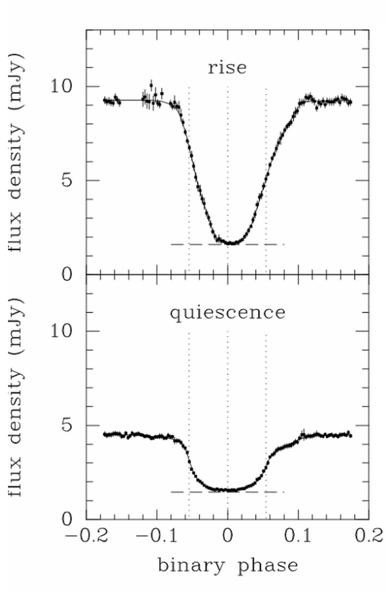

Figure 4: Eclipse profiles from Baptista & Catalan (2001). Data shown by dots, model – by line.

6. The Main Results of Our Photometrical Study of EX Dra

Some time ago Khruzina & Voloshina [23]. also provided a long-term photoelectric observations of EX Dra in quiescence, the pre-outburst state and outburst. These photometric observations were done on the 50 cm and 60 cm telescopes of the Crimean Astronomical station of the Sternberg Astronomical Institute. The detector which we used at the 50 cm telescope was an Apogee Alta U8300 CCD camera (3326 × 2504 pixels, 1 pixel=5.4 μm) with the sensitivity maximum being 60% at 5800-6600 A and 30% around 4000 A. The detector used at the 60 cm telescope was an Apogee 47 CCD device (1024×1024 pixels,1 pixel=13μm). The choice of the filter for observations was done on the sensitivity of the light detector used, which maximum was in the red region, R_c (λ = 6700Å). The uncertainty of a single estimation was $\Delta \sim (0.02 - 0.06)^m$. Since EX Dra was faint enough we used the exposure time varied from 40 to 60 s, depending on the sky conditions. About 24 observational sets with duration about $5^h - 8^h$ (to cover 1-1.5 orbital cycles) were obtained at R_c band in total during the period 2014-2016 (17 sets with 50 cm telescope and 7 sets — with 60 cm telescope). The overall light curve of EX Dra which shows the time distribution of all our observations in R_c band presented in Fig.5. Some of typical individual light curves one can see in the next Fig.6 during both quiescence and the active state. The observations at outbursts, when EX Dra brightness increases by $\sim 1^m - 1^m.2$ and the brightness at minimum increases by no more than $\sim 0^m.2 - 0^m.5$, clearly stand out. The total amplitude of the light curves is $\sim 1^m.7$ in quiescence and $\sim 2^m.5$ during outburst.

7. The Orbital Period

We determined the orbital period of the EX Dra system by our observations. The search for orbital period was done in the frequency range $(4.7 - 4.8)d^{-1}$ with a phase increment of 0.005^d.

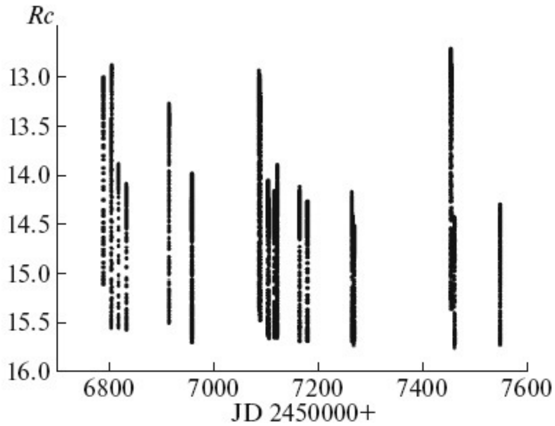

Figure 5: The overall light curve of EX Dra which shows the moments of our observations in R_c band

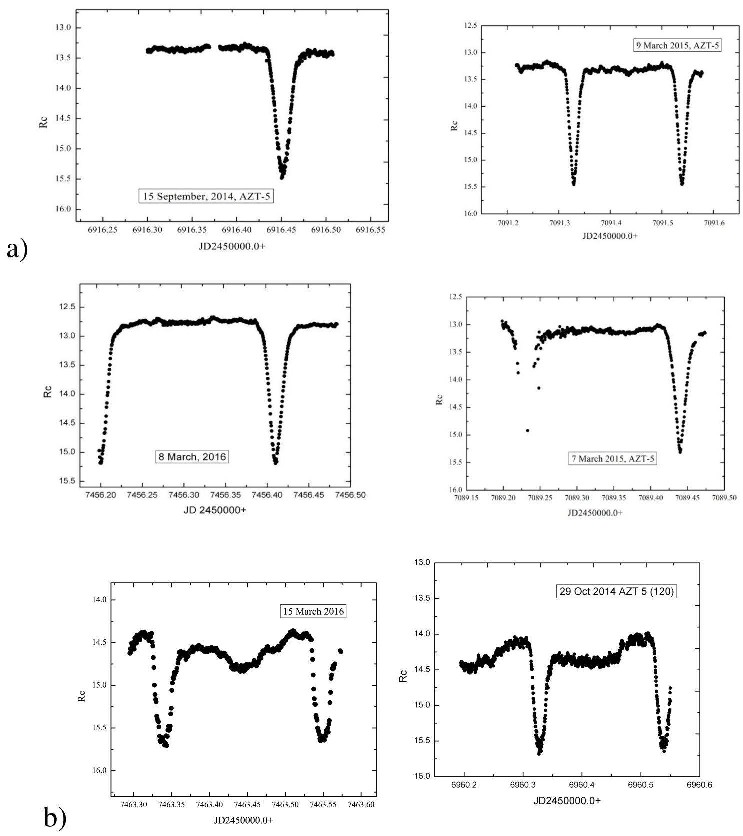

Figure 6: Some of the individual light curves of EX Dra obtained in active state (a) and quiescence (b)

The value of orbital period $P_{orb} = 0^d.2099366(6)$ was determined with the help of Lafler-Kinman method [24]. The power spectra constructed using our observations in R_c band is shown in Fig.7. The most prominent peak (shown by arrow) corresponds to the obtained value of the orbital period.

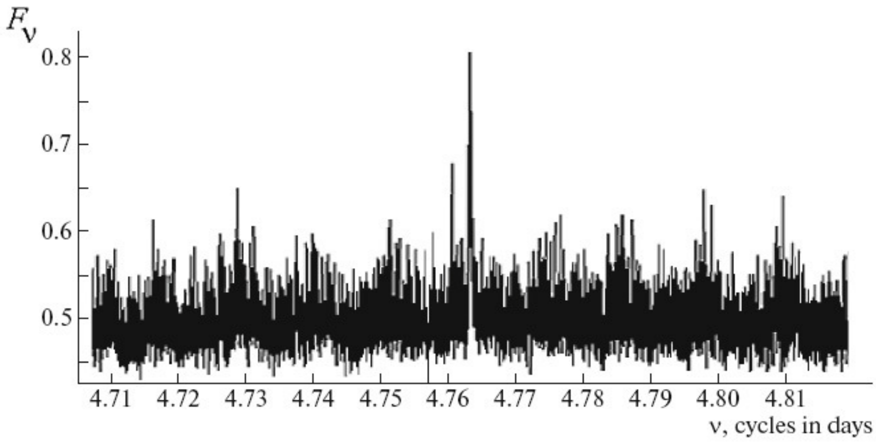

Figure 7: The Lafler-Kinman power spectra constructed using the observations in R_c band. The most prominent peak corresponds $P_{orb} = 0^d.2099366(6)$.

8. Determination of Binary Parameters

To fitting our observational lights curves by theoretical ones and determination of parameters of the system (both components, accretion disk, gaseous stream, hot line, hot spot) we consider a combined model that takes into account the presence of a hot spot on the lateral surface of the geometrically thick disk and of a region of enhanced energy release near the disk edge, at the base of the gas flow (the so-called "hot line"). A hot spot have a complex shape on the leeward side of the hot line. It is assumed that the thickness of the disk outer edge is highest in the region where the flow and disk collide, and decreases slowly on the leeward side, within the hot spot, to the unperturbed side. The entire part of the disk where its outer edge is thicker than the unperturbed disk is taken to belong to the hot-spot [25]. The results of the fitting of observational light curves by theoretical ones are shown by the example of two typical light curves selected from the entire massive of our observations, both at active and inactive states (see Fig.8). In this figure (upper panel) light curves of EX Dra constructed from our observations are presented: in quiescence and in outburst. Observations are shown by points, the theoretical curves — by the solid line. In the low panel of this figure contribution of various components to the total flux of EX Dra is shown.

The shape of the few light curves obtained in quiescence (so called anomalous) cannot be described in this standard model. In this case we used a model with the presence of dark spots on the secondary surface. Taking the existence of these spots into account, we were able to qualitatively reproduce the existence of secondary minima at phases differing from $\varphi \sim 0.5$. Results of our fitting of anomalous light curve as an example are shown in Fig.9. Non-ellipsoidal contribution of secondary radiation allows to describe anomalous minima at ~ 0.2 and ~ 0.7 phases (central panel). A schematic representation of such a system is shown in the panel on the right.

In the inactive state, the average contribution of the disk is comparable or slightly less than the average contribution of the secondary. The contribution of the white dwarf and the hot line is 5–10 times less. During outbursts, the flux from the disk increases 3–5 times and higher, completely determining the shape of the light curve of this system.

All parameters of EX Dra determined using these both models provide good accuracy in

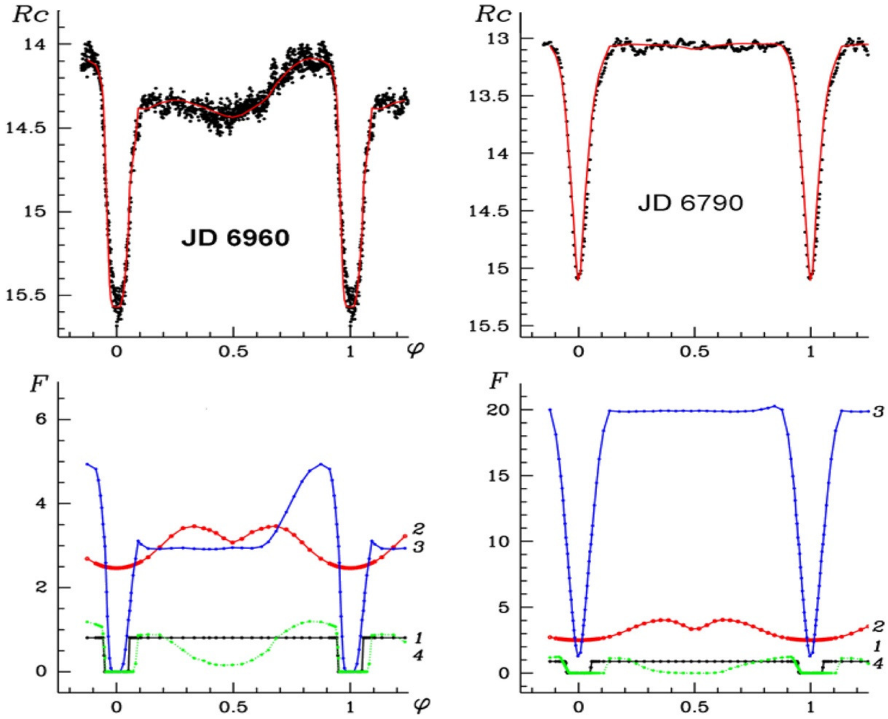

Figure 8: In upper panel: typical light curves of EX Dra in quiescence (on the left) and in outburst (on the right). Observations shown by points, theoretical curves — solid red line. In low panel – contribution of various components to the total flux of EX Dra for accordingly: 1 – white dwarf; 2 – red dwarf; 3 – disk with hot spot; 4 – hot line.

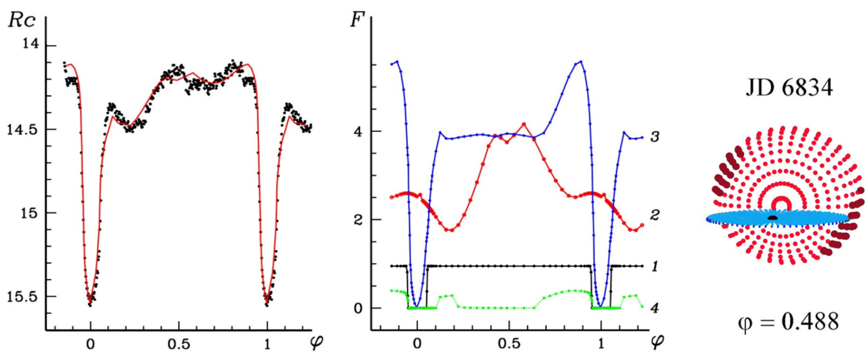

Figure 9: The results of fitting of EX Dra anomalous light curves in R_c. Left panel: observations shown points, the theoretical curve – by solid red line. Contribution of different components to the total flux of the system are shown on the central panel for accordingly: 1 – white dwarf; 2 – red dwarf; 3 – disk with hot spot; 4 – hot line. A schematic representation of such a system is shown in the panel on the right.

reproducing the system light curves in both states.

Some of the determined parameters of EX Dra are shown in the Table 2 below.

Table 2: Accretion disk and hot line parameters of EX Dra for quiescence and outburst

Parameter	Inactive state	Active state
$(R_d), a_0$	0.16 – 0.32	0.31 – 0.36
e	0.003 – 0.03	0.003 – 0.03
$0.5\beta_d^\circ$	0.5 – 1.7	0.6 – 1.6
T_{in} K	19100–25700	24200–33400
γ	0.43 – 0.58	0.24–0.42
$T(ww)$	29000–75600	33600–86500
$T(lw)$	31800–66500	30600–78900

T_{in} — temperature of inner regions of accretion disk, $T(ww)$ — temperature of windward side of gaseous stream, $T(lw)$ — temperature of leeward side of gaseous stream, β_d — thickness of the outer edge of accretion disk

The main results of eclipsing dwarf nova EX Dra photometric study by Khruzina et al. [23] could be summarized as follows: determination of the orbital period of EX Dra as $P_{orb} = 0^d.2099366(6)$ on the base of new photometric observations; fitting obtained observational light curves by theoretical ones in frame of combined model and determination of radiation parameters of this binary system in various states of activity. A few anomalous light curves could not be satisfactorily fit with theoretical ones in frame of combined model, worked out by Khruzina [25]. In this case, the existence one or two dark spots on the surface of the red dwarf secondary was added to this model. Taking the existence of these spots into account, the authors were able to qualitatively reproduce the existence of secondary minima at phases differing from $\varphi \sim 0.5$.

9. Summary

Thus, summing up our brief review of the properties of the eclipsing binary system EX Dra, we can conclude the following: currently, based on the numerous observations of this system in various spectral regions the statistical characteristics of EX Dra system are very well established, and it's physical parameters are determined fairly reliably. A number of important conclusions have been also drawn about the nature of outbursts in this system. Particularly important results among them are the detection of negative superhumps on the system's light curves and the conclusion that the outbursts in EX Dra belong to the "inside – out" type, as previously predicted by hydrodynamic studies of dwarf nova accretion disks and later confirmed by spectral observations of a number of similar systems [16].

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