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AN X-RAY AND OPTICAL STUDY OF THE UGSU-TYPE DWARF NOVA Gaia18awg

Oleksii Sokoliuk[1,2], Alexander Baransky[2], Andrew Khorolskiy[2], Volodymyr Vasylenko[2,3]
[1]*Main Astronomical Observatory of the NAS of Ukraine (MAO NASU), Kyiv, UA–03143, Ukraine,*
[2]*Astronomical Observatory, Taras Shevchenko National University of Kyiv, 3, Observatorna St., 04053 Kyiv, Ukraine,*
[3]*Astronomy and Space Physics Department, Taras Shevchenko National University of Kyiv, 60, Volodymyrska St., Kyiv, UA–01033, Ukraine,*
e-mail: oleksii.sokoliuk@mao.kiev.ua
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In this work we present optical, X-ray, and UV photometry, and X-ray spectroscopy of dwarf nova Gaia18awg (ASASSN-16le). We report an analysis of photometry, spectroscopy, and measurements of physical, orbital characteristics. Gaia18awg is a U Gem + SU UMa dwarf nova system. That system, showing non-periodic outbursts and superoutbursts, superhumps during superoutbursts. From the Lisnyky (MPC 585) data we determined the superhump period. This system shows positive superhumps with period 1.56 hr, respectively, and we identify an orbital the period of 1.51 hr. We determined the hitherto unknown mass of the secondary component, radii, and orbital characteristics. Analysis of the X-ray spectra showed strong Fe $K\alpha$ lines at 6.7–6.8 keV, Fe L complex around 1.1 keV, Ne $K\alpha$, Mg $K\alpha$, Si $K\beta$ lines with energies 0.9 keV, 1.3 keV, 1.83 keV, respectively. EPIC-pn, RGS photometry shows dominant soft X-rays during quiescence. We interpreted this as the radiation of the boundary layer.
Key words: astronomy, close binary, cataclysmic variable, X-rays.

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I. INTRODUCTION

Cataclysmic variables (CVs) are binary stellar systems with a massive and compact white dwarf as a main component and donor star (red, brown dwarfs of spectral class M–K, rarely a more massive star in the red giant branch with masses up to $\approx 10M_\odot$). In some of such systems, thermal instability of the accretion disk is present, which causes high rises in magnitude, namely outbursts, superoutbursts (which are characterized by a bigger magnitude difference, longer duration). Systems with these instabilities are oftenly referred to as Dwarf Novae (DNe) systems (for more detailed information, check [1, 2] and references therein). Also, it is worth noticing that transitions between outbursts and standstill periods are usually caused by the mass transfer rate rapid decrease.

It is interesting that among other CVs subclasses, dwarf novae have the biggest number of members, and according to the recent data, more that 50% of the cataclysmic variables belong to dwarf novae [3], and also most of the short period CVs (with $P_{\rm orb} \leq 2$ hr) are of SU UMa kind (DNe subclass). SU UMa cataclysmic variables as usual have outbursts and superoutbursts, which occur because of the combination of both thermal and tidal instabilities (tidal instability itself is caused by tidal forces of the main massive component). However, even if we generally understand the physical processes that cause a magnitude increase in DNe, details of these theories are still quite poorly undestood and need to be investigated.

There were a lot of sky surveys, which investigated dwarf novae. For example, in the last decades it was reported by Palomar–Green Survey and by Hamburg Quasar Survey that dwarf novae are based on their characteristic colors or emission lines [4, 5] [6, 7]. Also, a vast majority of dwarf nova systems were discovered by such sky surveys as Gaia, ASASSN, ZTF, Catalina Real-Yime Transient Survey (for more information about sky surveys, refer to [3]). In our paper, to probe the nature of the chosen dwarf nova system, we will be using three all sky surveys, namely ZTF (Zwicky Transient Facility), Gaia, ASASSN (All Sky Automated Survey for SuperNovae).

As for the object of interest, we have chosen faint dwarf nova Gaia18awg. This star was originally discovered as a variable by ASASSN Sky Patrol team on December 16, 2014, and was named ASASSN-16le. Only two years later, in October 7th, 2016, was ASASSN-16le successfully classified as a cataclysmic variable system, a candidate for the SU UMa subclass by Keisuke Isogai in VSNet-alert #20214. Finally, in the year of 2018, our object of interest was introduced in the Gaia Alerts database under the identificator Gaia18awg (until that time, for Gaia18awg two superoutbursts and four regular outbursts were observed).

Our article is organised as follows: in the first Section I we provide a brief introduction into the topic of cataclysmic variable stars, their classification, and introduce our object of interest. Section II consequently introduces the instrumentation that was used to obtain the results. In Section III, we analyse the data obtained from optical, and X-ray observations. In the Section IV we interpret the results, obtain a trigonometric periodogram, derive the orbital period, and component masses. Finally, we present the concluding remarks on the key topics of our study in Section V.

II. OBSERVATIONS

A. Lisnyky observations

We observed Gaia18awg using the 0.7-m reflector AZT-8 at the Kyiv Comet Station (MPC code 585) with the FLI PL 47-10 CCD camera located in the prime focus ($F = 2828$ mm) of the telescope and equipped with Johnson–Cousins U, V, R, B, I broadband filters. The detector consists of a 1024×1024 array of 13 µm pixels, which corresponds to a scale of 0.947″ per pixel. The estimated readout noise is about 10 $\bar{e}$ and the conversion gain is about 1.2 $\bar{e}$ /ADU.

The Gaia18awg observational campaign was started in the year of 2019; from that time we were observing Gaia18awg constantly, generally using sub-expositions of 1990s. Results of our light curve data analysis were published in the AAVSO/BAA databases.

B. XMM-Newton observations

Gaia18awg was observed using the EPIC-MOS1/2, EPIC-pn (European Photon Imaging Camera), RGS (Reflection Grating Spectrometer), OM Telescope (Optical/UV Monitor Telescope) of the XMM-Newton observatory (ObsID 08711910011) on 2020 June 21 (MJD 59021) for about 16 ks. Exposure for X-ray images — about 16600s, for OM images — 3600–4000 s per image. For near-UV and optical observations at the OM instrument, we used photometric bands U, V and ultraviolet UVW1 band. On the other hand, for EMOS1/2 and EPN intruments we were using both small and large window modes with a medium filter. Finally, at the grating, X-ray spectrometers HER+SES mode were used.

C. Neil Gehrels Swift observations

Swift Space Telescope observed Gaia18awg on May 20 2020 (MJD 58989) for about 1.2 ks. BAT (Burst Alert Telescope), XRT (X-Ray Telescope), UVOT (Ultraviolet/Optical Telescope) instruments were used in the observations. For the main SWIFT instrument, the XRT regular mode weas used, namely the Photon Counting (PC) mode. For BAT we set Burst/Survey mode, since this instrument has a large field of view to detect X-Ray transients. For the Ultra-Violet detector we used band W2. ,

III. DATA ANALYSIS

A. Methods of data analysis

Generally, to obtain an optical light curve from the AZT-8 telescope data, we were using python libraries such as LightKurve, astropy, astroquery, astrocut. The reference stars were objects from the *APASS DR10* catalog (The AAVSO Photometric All Sky Survey), magnitudes for reference stars were taken from the Aladin or from AAVSO star maps, which select reference stars on the basis of temperature, and spectral class. The *APASS DR10* catalog includes magnitudes of stars from about 7th magnitude to about 17th magnitude in five filters: Johnson B and V, plus Sloan u', g', r', i' and z' [8]. It has mean uncertainties of about 0.07 mag for B, about 0.05 mag for V, and less than 0.03 mag for r. To derive the magnitudes of reference stars from the *APASS DR10* catalogue, we have used the methods, described in the [9]. The periodicity of the photometric signal was analyzed using Multi-Column View [10, 11] astronomical software. Superhump polynomial models were created using numpy+curvefit libraries. X-ray observations on the BAT detector (10–150 keV), XRT (0.3–10 keV), and on the XMM-Newton space telescope (0.3–12 keV) were processed and analyzed using CIAO code, SAOImage DS9 + SAS programs (Linux Ubuntu 20.04LTS), HEASARC XSPEC.

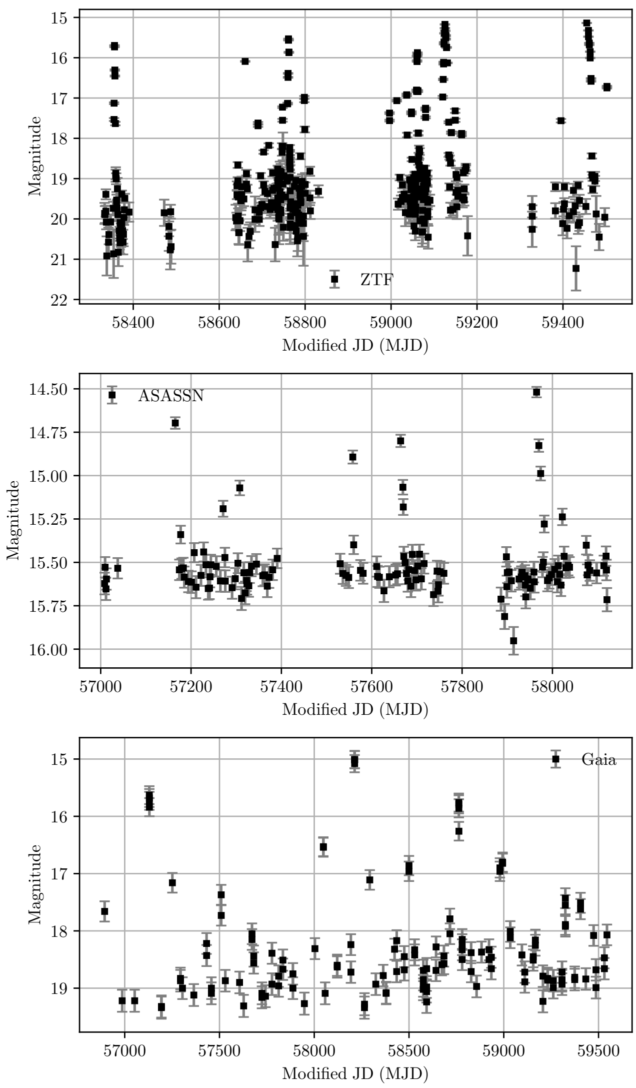

Fig. 1. Observations of Gaia18awg by the various sky surveys, such as ASASSN, ZTF and Gaia

B. Gaia18awg in the light of sky surveys

Ground-based and space observatories (such as the Lisnyky Observatory, Terskol, Palomar (ZTF), ASASSN, Gaia) have been monitoring Gaia18awg since 2014. Since that time, large numbers of outbursts and superoutbursts have been detected for Gaia18awg. On May 10 and 24 2020, the Gaia Space Observatory recorded two outbursts, between which there was a record short quiescent period (a period of the so-called standstill of the system between outbursts). Usually, outbursts in the Gaia18awg and other DNe, SU UMa binary stellar systems occur every 3–4 months. Palomar Observatory used a 1.2-m telescope to confirm the Gaia Observatory data.

We plot the whole observation history for the Gaia18awg transient till the recent time on Fig. 1. We noticed that judging by the observational log, there are 6 superoutbursts, 1 double outburst, 11 outbursts (total 13O, 6SO) present at the moment. According to curves from Fig. 1, Gaia18awg can be classified as a star of class SU UMa, as this stellar system has frequent outbursts and more rare superoutbursts, during which superhumps could occur. No periodicity of outbursts or superoutbursts in the Gaia18awg observations was detected, which is an expected behavior of CVs.

C. Lisnyky photometry of Gaia18awg during the superoutburst phase

On Figure 2 we properly plotted the Gaia18awg light curve in the Johnson-Cousins R photometric filter that was obtained on February 9, 2020, between 17:30 (UT) and 20:30 (UT) at the Lisnyky observatory. Gaia18awg was in the superoutburst phase, judging by the magnitude and present positive superhumps, which could be easily observed on the provided light curve. For a dwarf novae subclass, superhumps could be caused by the scattering of viscosity of the gas in the accretion disk due to its periodic deformation, which is associated with the orbital period.

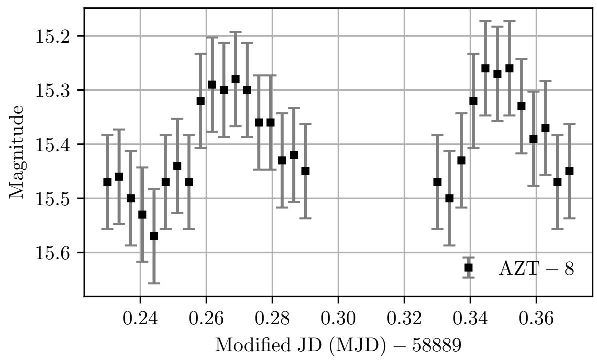

Fig. 2. Gaia18awg 9 Feb., 2020 observations the Lisnyky observatory, Johnson–Cousins R band with $\pm 1\sigma$ errors

D. XMM-Newton X-ray spectroscopy analysis

Gaia18awg X-ray spectrum was obtained from the observations of RGS1 + RGS2 grating spectrometers, instruments of the XMM-Newton space telescope. The Gaia18awg spectrum is very similar (have the same emission/absorption lines) to the spectrum of the closest by characteristics systems (cataclysmic variables of SU UMa, UGSU type with orbital period $P_{\mathrm{orb}} < 3h$, such as V344 Lyrae [12].

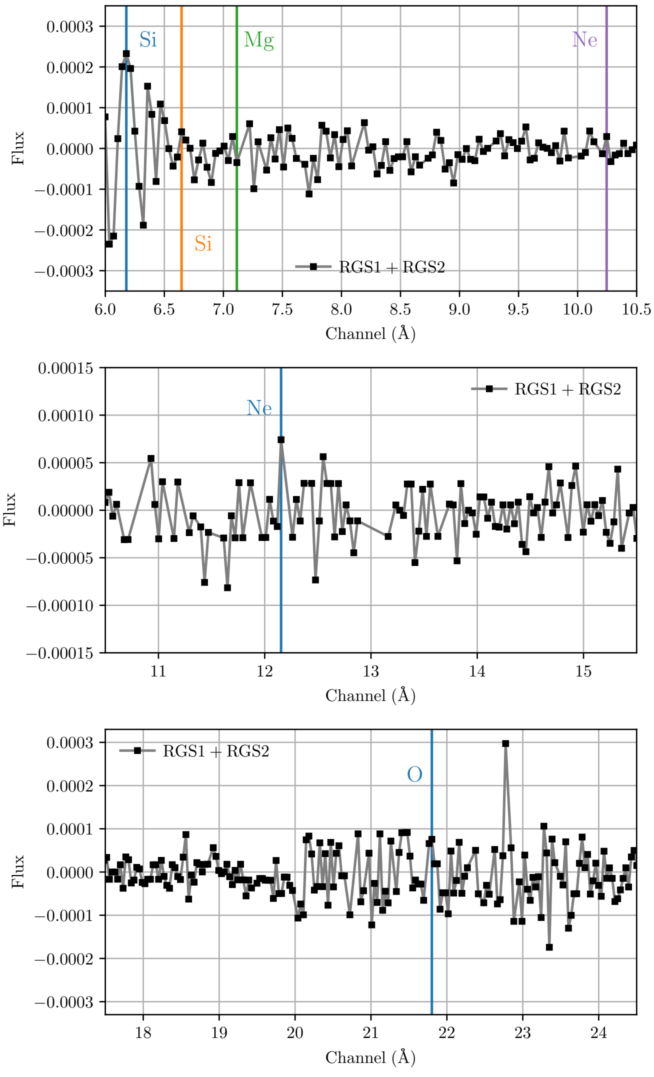

Fig. 3. Normalized flux X-ray spectrum of Gaia18awg (6–37 Å with emission/absorption elements)

Flux Gaia18awg spectrum on RGS1/2,EPIC PN detectors was obtained by processing ODF (Observation Data File) calibrated data and generating high-quality PPS (Processing Pipeline System products) data with the substracted background noise. Standart XMM-Newton SAS/XSPEC data processing procedures were used in the PPS processing. Here and further, the flux of the point source weas measured in the units of erg/cm^2/s.

According to the X-ray spectral analysis of the RGS data from the XMM-Newton space telescope (see Fig. 3), the Gaia18awg system contains such chemical elements as Silicium, Magnesium, Neon, Oxygen (it is unclear whether Magnesium and Oxygen lines are present in the spectrum because of the low system magnitude and therefore high noise level). For a regular example of X-ray spectra for CVs refer to the Koji Mukai work [13].

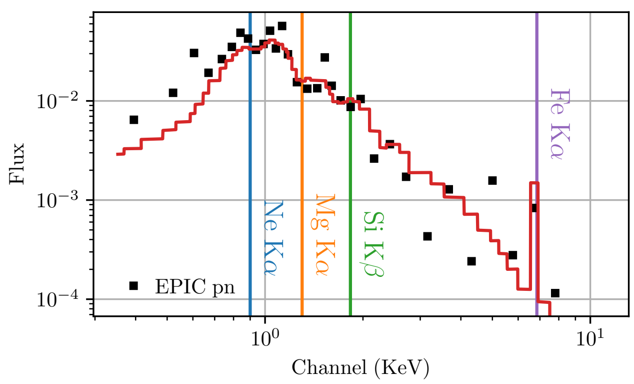

Fig. 4. EPIC-pn spectrum with cemekl+pwab model and markered emission elements

On the other hand, on Fig. 4 we showed the EPIC-pn X-ray spectrum with the HEASOFT XSPEC model (combined model of multi-temperature emission of plasma `cemekl` [14] and the model of power distribution of neutral absorbers `pwab` [15]). The best-fit model values are therefore: $T_{\max} \approx 5.27 \pm 3.12\,\mathrm{keV}$, $nH_{\min}(10^{22}) = 1.706 \cdot 10^{-3}\ \mathrm{cm}^{-2}$, $nH_{\max}(10^{22}) = 0.8474\ \mathrm{cm}^{-2}$. The aforementioned figure shows the lines of radiation (emission), up to 2.5 keV, where the spectrum of hot diffuse plasma elements and X-rays from the boundary between the inner radius of the accretion disk and the white dwarf (the main component of the system) are usually detected. Soft X-rays could be present in the energy range from 0.08 to 2.5 keV due to the difference in the rotational speeds of the white dwarf and the accretion disk (the accretion disk moves at Kepler speeds and a white dwarf often rotates slower).

In the EPIC-pn spectrum of Gaia18awg (during relative standstill period), we detected strong Fe $K\alpha$ lines in the range from 6.7 to 6.8 keV [16], Fe L complex with energy 1.1 keV [17], Ne $K\alpha$ emission with energy $\approx$ 0.9 keV, Mg $K\alpha$, and Si $K\beta$ lines with energies ≈ 1.3 keV and ≈ 1.83 keV, respectively [18]. The energies of the available emission lines in the EPIC-pn spectrum of Gaia18awg completely coincide with the tabular values of $K\alpha$ and $K\beta$ energies of the elements. The tabular values were determined by using the well-known Siegbahn notation. Also, the spectrometric data obtained from the XMM-Newton Space Telescope observations on RGS/EPN instruments coincide well with the data obtained by other authors for other cataclysmic variable stars. Identical emission lines were detected in the X-ray spectrum of CV SS Cyg [19] and weakly magnetic CV EX Hya [20].

E. X-ray and UV photometry analysis

X-ray photometry has always been an important addition to optical and infrared photometry. The most important and massive events in the life of many objects in the universe (quasars, close binary systems, etc.) took place with the formation of large amounts of X-rays; so the study of the phenomena through which it is formed is very important for modern astronomy. During this study, Gaia18awg was observed using two X-ray telescopes (XMM-Newton, Swift). Observations were performed during the relative standstill and double outburst phase on June 21, and May 21 respectively. Gaia18awg Swift Observation TargetID was 13502, XMM-Newton Obs.ID — 08711910011. The observation data on EPIC-PN, RGS intruments were processed using standard operations, such as: evselect, epiclccorr, rgslccorr, xmmselect. The PPS data were generated based on calibrated ODF event data files. All curves presented in the article are generated with the substracted background. On May 20, 2020, Swift Space Telescope observed the cataclysmic variable Gaia18awg under the TOO (Target Of Opportunity) program, and due to a double outburst (because of the lack of data, we cannot say for sure whether it was a double outburst or just an abnormally long single outburst, but further we will call this event a double outburst) that occurred between May 10 and 27, the XMM-Newton Space Telescope also observed the star on June 21. 2020. According to XRT, the average count rate for Gaia18awg on May 21 was approximately $0.0181 \pm 0.0046\,\mathrm{ct/s}$.

Bursts in soft X-ray were detected on the X-ray curves (for graphical representation of X-ray curves, refer to Figure (8)). These bursts are similar to the orbital modulation in Soft X-rays/EUV detected in the magnetic CV AM Her [21] and to the non-periodic spin modulation at quiescence [22], although all of these modulations are most often found only in magnetic CVs and polars. The closest possible version of the nature of these bursts is the interaction of the boundary layer of the accretion disk with the white dwarf. The boundary layer emits more than half of all accretion luminosity in a soft X-ray [23].

Judging by the Optical/UV photometry from UVOT (total exposure images with WCS grid are shown on Fig. 6), in the U filter the magnitude was 17.67±0.08 (AB), in the V filter, 16.97 ± 0.05 (AB), and in the ultraviolet UVW1 band, therefore, 16.71 ± 0.13 (Inst.). These magnitudes for our object of interest generally correspond to the post-outburst stage. Keeping that fact in mind, boundary layer emission usually occurs in a soft X-ray range; so the aperiodic bursts on RGS1/2 X-Ray photometry from Fig. 5 could be explained by boundary layer bursts. If the cataclysmic variable is in the active phase, boundary layer energies of radiation will shift to the hard X-rays/Gamma. Figure 7 clearly shows that almost all Gaia18awg radiation is concentrated in soft X-rays up to 2 keV (In RGS the curve is almost identical with the energy range 0.33–2.5 keV). Also in Fig. 7 a radiatilon continuum of 0.05 ct/s (red shaded area) was found which was detected in all energy ranges. We also marked the area with high errors from the background noise with gray shadow (such an unexpected behavior of the light curve in the range from 14500 to 16000 s could be explained by the rise of background noise, which could not be deleted).

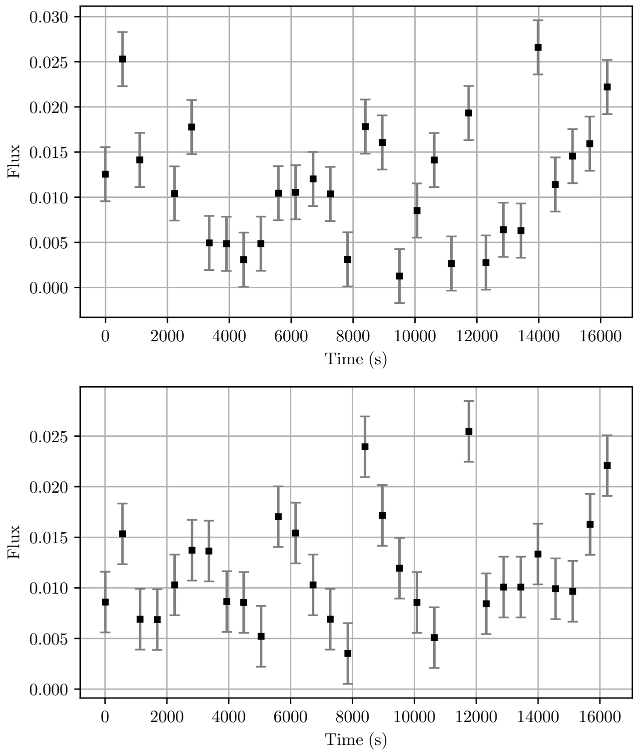

Fig. 5. RGS/PN X-ray photometry with polynomial models

IV. RESULTS AND DISCUSSION

A. Lisnyky photometry results. Periodogram construction

As we already mentioned in the previous sections of the paper, in our photometry during Gaia18awg's superoutbursts, so-called positive superhumps were detected. Superhumps usually occur during the superoutburst phase in SU UMa dwarf novae. From the superhump period, we can derive orbital period by empirical or semi-empirical relations. Obviously, an orbital period is the period during which the celestial body makes one complete turn around the common center of mass in binary systems. In NL (nova-like variables), orbital period $P_{\rm orb}$ is mostly greater than 3 hours; due to this in NL a large value of $\dot{M}$ (mass-accretion rate), and a large loss of angular momentum (J) with time present. Systems with an orbital period $P_{\rm orb}$ shorter than 2 hours are mainly classified as DN (dwarf nova). Significantly fewer systems occur in the "period gap", which is between 2 and 3 hours. About half the stars in the period gap are magnetic systems (most of which are polars), and the other half are SU UMa systems, which are characterized by outbursts and superoutbursts.

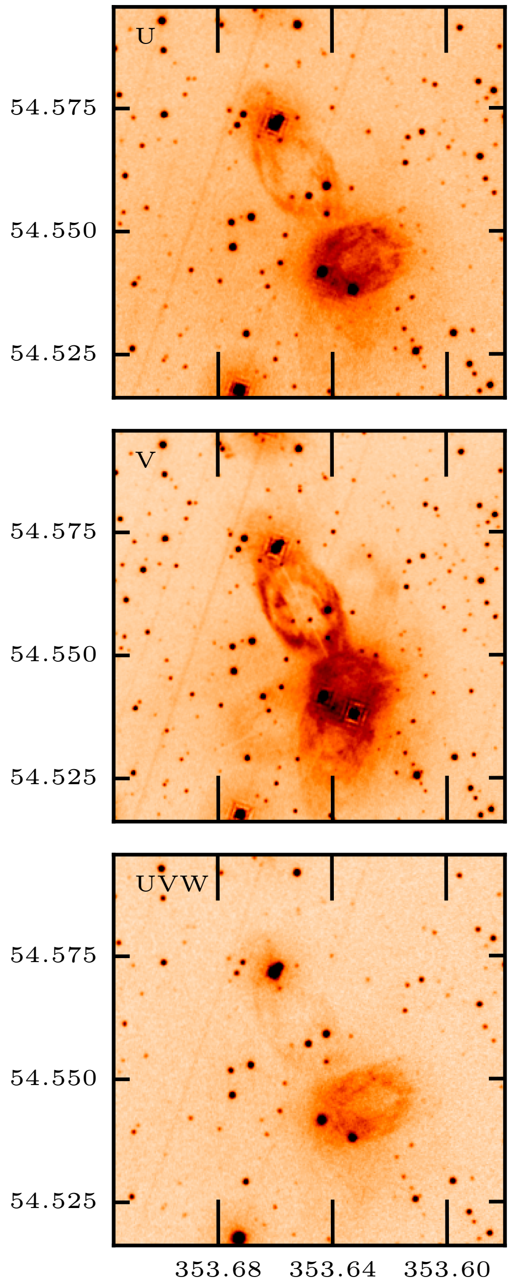

Fig. 6. Images of the Gaia18awg taken with the help of UVOT detector and various photometric filters. On the both axes, there are source coordinates given in the units of R.A., Dec. degrees

The orbital period can be determined from the light curve, if the binary system is an eclipsing one. Also, the orbital period is determined by its dependence on the period of superhumps. In turn, the period of superhumps is determined by the DFT periodogram (Discrete Fourier transform) [24] and Lomb–Scarle periodogram [25, 26]. Also, for sky surveys (where single-star observations are non-periodic and sometimes time intervals between

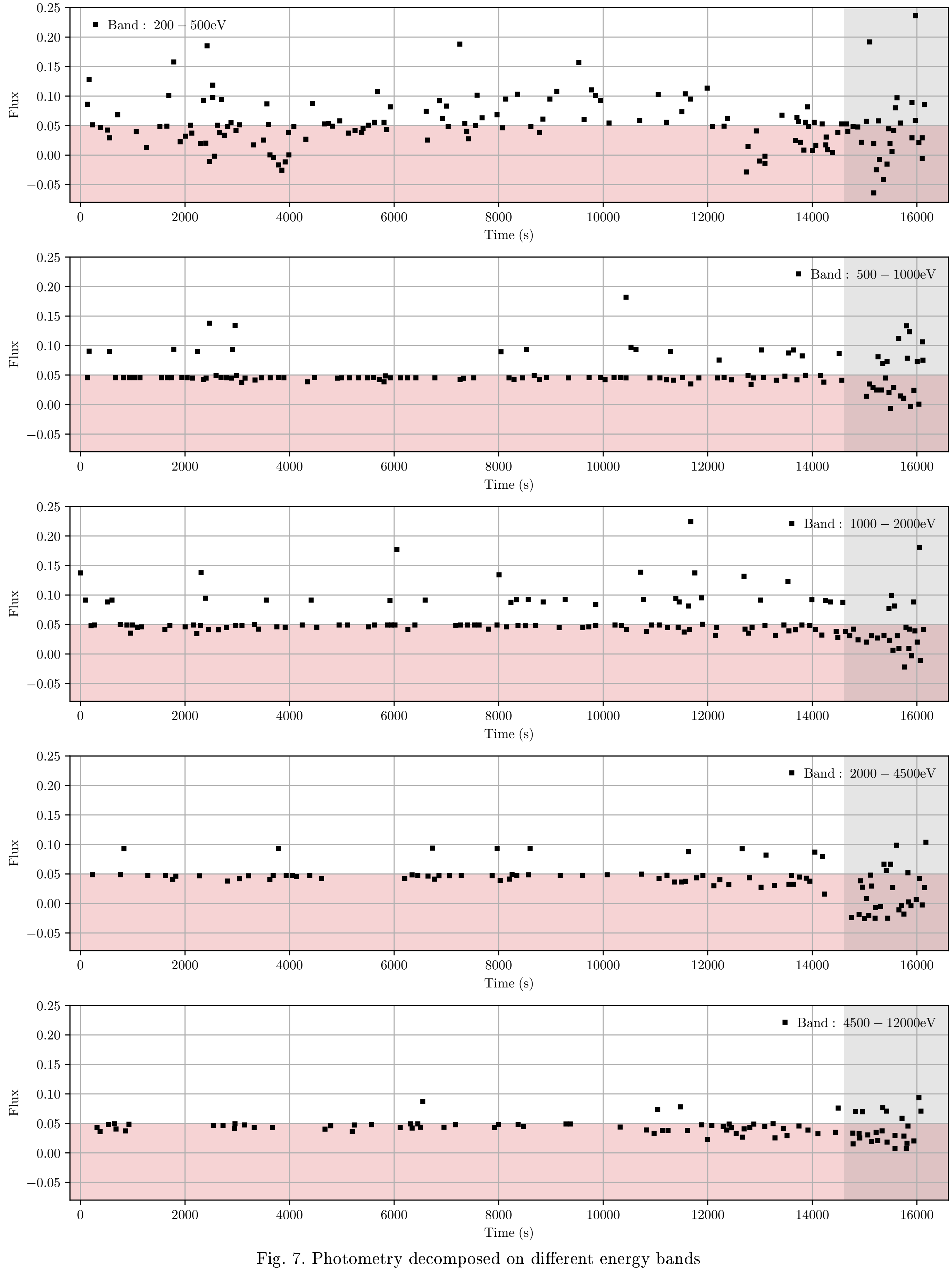

Fig. 7. Photometry decomposed on different energy bands

observations are very large), in addition to the Lomb–Scargle analysis, the so-called FTP (Fast Template Periodogram) [27] could be used. In our study, we used the Andronov periodogram method with linear detrending and trigonometric polynomials with different degrees of approximation [10, 11]. Trigonometric polynomial fit is generally given as follows [28]:

$$x(t) = C_1 + \sum_{j=1}^{s} (C_{2j} \cdot \cos(2\pi f j(t - \bar{t})) + C_{2j+1} \cdot \sin(2\pi f j(t - \bar{t})), \quad (4.1)$$

where $\bar{t}$ is the sample time mean value, $f = 1/P$ is frequency, and C_α are the coefficients computed from the method of least squares (MLS). It also will be helpful to define the test function [29]:

$$S(f) = \frac{\sigma_C^2}{\sigma_O^2} = r^2, \quad (4.2)$$

where σ_C^2, σ_O^2 are variances of the values for some function calculated from trigonometric fit and observed, and r^2 is a square of the correlation coefficient between the observed and calculated values. [28]. For the Gaia18awg photometry we used "Multi Column View" software, which was described in detail in the work of [10].

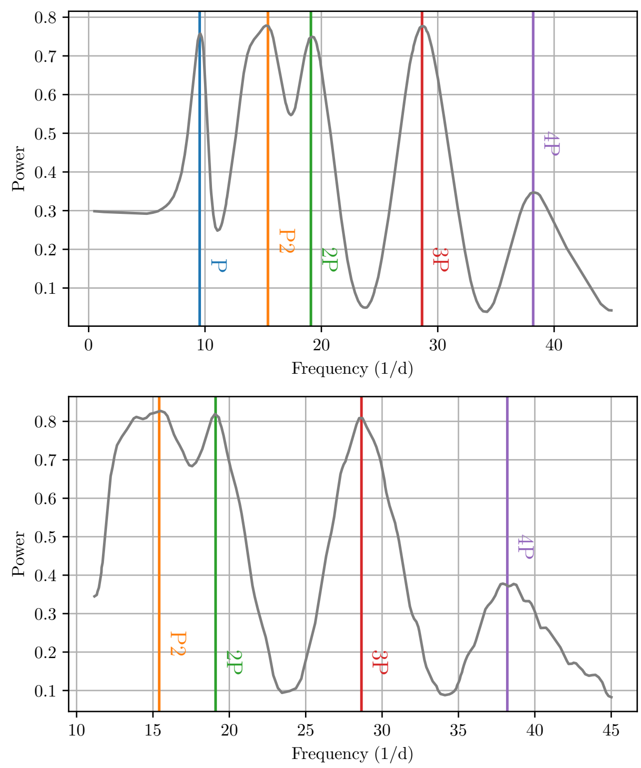

Fig. 8. Periodogram with numbered highest peaks and trigonometric polynomial degrees on it.

On the periodogram from Fig. 8, one can notice two plots with trigonometric polynomial degrees 2 and 8, respectively. $P2$ is the highest peak, $2P$, $3P$ and $4P$ are harmonics of the first peak P. The highest peak and the estimated period of superhumps had frequency 15.36 which corresponds to period 0.065104d. Therefore, for our DNe, the estimated period of superhumps from observations is $P_{\rm sh} \approx 0.0651$d ≈ 1.5625h. Since we already derived period of positive superhumps, we now could as well derive the orbital period of the system. The easiest way to do this is to derive $P_{\rm orb}$ from the period of superhumps $P_{\rm sh}$ and the period of nodal precession of the accretion disk (nodal precession is the displacement of the orbital plane of the accretion disk relative to the white dwarf due to the non-sphericality of the disk itself (in the disk, the gravitational field is divided unevenly) [30, 31]:

$$P_{\rm prec}^{-1} = P_{\rm orb}^{-1} - P_{\rm sh}^{-1}. \quad (4.3)$$

Cataclysmic variable stars with a relatively small orbital period ($P_{\rm orb} < 4$h) may exhibit superhumps — photometric waves, with a period that is slightly smaller or larger than the orbital. Superhumps are currently found in a large number of cataclysmic variables, and are more typical for of nova systems. The most common are positive superhumps (where $P_{\rm sh} > P_{\rm orb}$), which occur due to the prograde precession of the accretion disk [31, 32]. Most often, the period of nodal precession of the accretion disk can be determined by the sinusoidal signal on the curve during a superoutburst or an outburst in dwarf nova systems (sinusoidal signal has a small amplitude and a large (several days) period). Gänsicke derived an empirical relationship between the period of superhumps and the orbital period [33, 34]:

$$P_{\rm orb} = 0.9162 P_{\rm sh} + 5.39. \quad (4.4)$$

According to Equation (4.4), the orbital period of the Gaia18awg system is $P_{\rm orb} \approx 0.0632$d ≈ 1.519h. According to the orbital period of 1.519 hours and the light curve, the dwarf nova Gaia18awg can be classified as a cataclysmic variable of the SU UMa class.

B. Determination of the Gaia18awg system characteristics

To determine the mass of the second component, we used equation [35]:

$$M_2 = (0.0069/P_{\rm orb}[d]^{1.22})\alpha^{1.83}. \quad (4.5)$$

For Gaia18awg parameter $\alpha \equiv 1$, $M_2 \approx 0.20043 M_\odot$ The relation between the orbital period and mass, radius of second component [35] is:

$$P_{\rm orb}[\rm h] = 8.75(M_2/R_2^3)^{-1/2}. \quad (4.6)$$

From Equation (4.6), $R_2 \approx 0.18792 R_\odot$. The fractional period excess could be determined by [36]:

$$\varepsilon = 0.18q + 0.29q^2 = \frac{P_{\rm sh} - P_{\rm orb}}{P_{\rm orb}}, \quad (4.7)$$

where

$$q = \frac{M_2}{M_1}, \qquad M_1 = \frac{M_2}{q}. \quad (4.8)$$

Via (4.7) $\varepsilon = 0.0286$, from (4.8) $q \approx 0.158$.

V. CONCLUSIONS

We presented the results of X-ray, optical observations, photometry, and spectroscopy data analysis of the Gaia18awg DN system. Our main results are:

1 The orbital and superhump periods are $P_{\rm orb} \approx 1.519\,{\rm hr}, P_{\rm sh} \approx 1.562\,{\rm hr}$, giving a superhump period excess $\varepsilon \approx 0.0286 \approx 2.86\%$.
2 The mass of the donor is $M_2 \approx 0.2004 M_\odot$ and the mass ratio $q \approx 0.158$.
3 The radii of the secondary is $R_2 \approx 0.18792 R_\odot$.
4 From the EPIC-pn and RGS X-ray spectrum, we determined the energies of the emission elements. The X-ray spectra showed strong Fe $K\alpha$ lines at 6.7–6.8 keV, Fe L complex around 1.1 keV, Ne $K\alpha$, Mg $K\alpha$, Si $K\beta$ lines with energies 0.9 keV, 1.3 keV, 1.83 keV respectively.
5 EPIC-pn, RGS photometry shows dominant soft X-rays during quiescence. We interpreted this as the radiation of the boundary layer.

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РЕНТҐЕНІВСЬКЕ ТА ОПТИЧНЕ ДОСЛІДЖЕННЯ КАРЛИКОВОЇ НОВОЇ Gaia18awg ТИПУ UGSU

О. Соколюк[1,2], О. Баранський[2], А. Хорольський[2], В. Василенко[2,3]
[1] *Головна астрономічна обсерваторія Національної академії наук України (ГАО НАНУ), Київ, 03143, Україна,*
[2] *Астрономічна обсерваторія, Київський національний університет імені Тараса Шевченка, вул. Обсерваторна 3, Київ, 04053, Україна,*
[3] *Відділ астрономії та космічної фізики, Київський національний університет імені Тараса Шевченка, вул. Володимирська 60, Київ, 01033, Україна*

У цій роботі описано оптичну, рентґенівську та ультрафіолетову фотометрію, рентґенівську спектроскопію карликової нової Gaia18awg (ASASSN-16le). Проаналіззовано фотометрії та спектроскопії, вимірювання фізичних, орбітальних характеристик системи. Gaia18awg — це гібридна система, що поєднує в собі класи U Gem та SU UMa. Ця катаклізмічна змінна показує неперіодичні спалахи та надспалахи, надгорби під час надспалахів, що й очікувано від карликової нової. Надгорби мають період 1.56 годин, що вказує на орбітальний період у 1.51 години. У додаток до орбітального періоду визначено масу зорі-донора, її радіус та піввісі орбіти. Аналіз рентґенівського спектра показав сильні емісійні лінії Fe $K\alpha$ з енерґією 6.7–6.8 keV, Fe L-комплекс поблизу 1.1 keV, Ne $K\alpha$, Mg $K\alpha$, Si $K\beta$-лінії з енерґіями 0.9 keV, 1.3 keV, 1.83 keV відповідно. Фотометрія EPIC-pn, RGS показує домінантне м'яке рентґенівське випромінювання під час фази відносного спокою. Ми інтерпретували це як випромінювання прикордонного шару диска акреції.

Ключові слова: астрономія, тісна бінарна система, катаклізмічна змінна, рентґенівське випромінювання