АСТРОФИЗИКА

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ULTRAVIOLET SPECTRAL EVOLUTION OF V1974 Cyg USING IUE LOW RESOLUTION SPECTRA

G.M.HAMED[1], M.R.SANAD[1], A.ESSAM[1], S.YOUSEF[2]

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We investigated the spectral evolution of some normalized UV emission lines through different stages of the outburst of the classical nova V1974 Cyg using International Ultraviolet Explorer (IUE) low resolution short wavelength spectra. The emission line fluxes were calculated and used to estimate the ultraviolet luminosity of the emitting region and the latter is used to determine the average mass accretion rate during the post-nova phase. We found an average value of the ultraviolet continuum luminosity $L_{cont} \sim 4.6 \pm 0.4 \times 10^{35}$ erg s^{-1} and the average mass accretion rate $\dot{M}_{acc} \sim$ $\sim 6.6 \pm 0.6 \times 10^{-10}\ M_{\odot}$ yr^{-1}. We used the fitted continuum luminosity to estimate the temperature of the central white dwarf and we found an average value of $\sim 3 \times 10^5$ K. The spectral behavior is attributed to the variation in the opacity, temperature and density of the ejecta during the different phases of the outburst. Our results are consistent with the theoretical ONe classical nova models.

Key words: *novae: cataclysmic variables - stars: Individual (V1974 Cyg) - ultraviolet: stars - white dwarfs*

1. *Introduction*. Cataclysmic variables (CVs) are semidetached binary stars where a white dwarf accretes matter from a late type main sequence star via Roche lobe overflow through the inner Lagrangian point. Due to the high angular momentum of the falling gas stream, matter doesn't fall directly to the star and forms an accretion disk.

Classical novae are a class of cataclysmic variables where only one outburst has been observed. During this outburst the magnitude difference is between 6 and 19 mags from the prenova state. It is widely accepted that this outburst is a result of thermonuclear runaway of the matter accreted on the surface of the white dwarf [1].

It has been proposed that most of the mass of the envelope accreted on the surface of the white dwarf is ejected in the form of optically thick wind (see e.g. [2,3]). The time required for a nova to decline 3 magnitudes below its visual maximum (t_3) is used to classify novae to different speed classes.

The study of the outburst of classical novae is very important in astrophysics since it provides us with an opportunity to understand the evolution of close binary systems, the nature of white dwarfs, thermonuclear runaway processes and the hydrodynamics of the explosion.

The outburst of a classical nova can be divided into different stages. After the explosion, the "fireball phase" starts where the shock resulting from the explosion heats the ejecta which is expanding freely and cooling. During this phase the opacity is high in both line and continuum. The second stage is the iron curtain where the cooling of the ejecta leads to the recombination of the iron peak elements leading to the screening of other lines in the spectrum. The third stage is "lifting the iron curtain" which is characterized by the retreat of the pseudo-photosphere leading to the enhancement of ionization and the disappearance of ultraviolet absorption lines. The opacity of the ejecta then decreases and semi-forbidden lines start to appear marking the "transition stage". The nebular phase is characterized by the appearance of strong forbidden lines in emission. Then the spectrum enters the post-nova stage [4-7].

A wide range of intercombination, resonance and forbidden lines for many elements can be found in the ultraviolet spectra of novae, some of these lines are characteristic of some of the different stages of the outburst. The study of these line provides us with an opportunity to understand the physical conditions of the ejecta and determine the elemental abundances accurately [8].

The outburst of V1974 Cyg (Nova Cygni 1992) was discovered on Feb 19th 1992 by Collins et al. [9] at a visual magnitude of 6.8 mag. It reached a maximum visual magnitude of 4.4 mag three days later. Its visual magnitude declined by 3 magnitudes 42 days after maximum making it a fast nova [10]. It is a well studied classical nova with multiple observations in different bands. There are some estimates of the V1974 Cyg distance. In our investigation we adopt a value of 1.8 ± 0.1 kpc which is consistent with the distance determined from the MMRD relations and expansion parallax method [11-13]. We adopt an E(B-V) value of 0.35 mag [14].

In this paper, we present IUE low resolution ultraviolet spectra for V1974 Cyg. In Section 2 we present the spectra and data reduction. Main results are presented in Section 3. We discuss these results in Section 4. Section 5 contains the conclusions.

2. *Observations and Data Reduction*. In this paper, we used International Ultraviolet Explorer (IUE) spectra of V1974 Cyg. These observations were taken by the short wavelength prime camera (wavelength range from 1150 to 2000 Å) with the large aperture (a 10 by 20 arcsecond slot) and low resolution (~6 Å). We downloaded the files from the IUE Newly Extracted Spectra (INES) server at http://sdc.cab.inta-csic.es/ines/. The observations cover the period between 20/02/92 and 20/11/94. Table 1 contains the journal of the used spectra. Good care was taken in inspecting the spectra and the ones with significantly high noise or saturated pixels were excluded where we made use of the quality column in the FITS files of the spectra guided by Table 1 in [15]. All the spectra were

Table 1

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Spectrum JD	ID- 2440000	Exposure Time (s)	Spectrum ID	JD- 2440000	Exposure Time (s)	Spectrum ID	JD- 2440000	Exposure Time (s)
44030	8673.4	9	44389	8725.8	29	46404	8960.9	129
44031	8673.5	44	44439	8732.8	39	47027	9041.7	269
44040	8674.5	419	44632	8752.3	39	47278	9061.5	269
44043	8675.2	479	44634	8752.4	19	47397	9078.3	269
44044	8675.3	2099	44717	8761.7	29	47416	9082.3	269
44050	8676.4	179	44761	8767.7	29	47417	9082.3	599
44051	8676.7	59	44762	8767.7	44	48026	9171.0	1139
44055	8677.6	29	44790	8770.3	29	48027	9171.1	3599
44056	8677.7	119	44808	8772.6	29	48028	9171.2	1139
44060	8678.6	49	44901	8783.3	34	48218	9192.4	1799
44062	8678.7	179	44937	8790.2	37	48219	9192.5	3599
44064	8678.9	59	44970	8794.4	34	48220	9192.6	6599
44073	8680.4	39	44973	8795.6	34	48221	9192.8	1379
44086	8682.8	49	45030	8802.6	37	48222	9192.8	1499
44102	8684.5	19	45059	8807.2	41	48638	9246.2	1799
44115	8686.3	34	45061	8807.3	39	48639	9246.3	4499
44130	8688.8	34	45135	8818.2	50	49320	9317.0	3599
44155	8693.5	34	45244	8833.1	59	49321	9317.2	7199
44174	8695.7	34	45310	8845.0	79	49322	9317.3	3299
44193	8700.5	34	45359	8851.4	59	50494	9449.7	16499
44209	8703.9	34	45469	8864.4	69	50941	9503.6	20399
44233	8707.5	29	45547	8873.0	109	51387	9543.8	20695
44268	8711.9	29	45548	8873.0	99	51983	9594.4	25199
44305	8715.3	29	45670	8883.3	109	52846	9677.5	24599
44338	8717.8	29	46047	8919.1	169			
44377	8723.4	29	46064	8921.6	114			

normalized using the continuum task in onedspec package of the Image Reduction and analysis Facility (IRAF). The continuum was best fitted by a Chebyshev function of the fifth order and the emission line properties were measured from the normalized spectra.

3. *Results*. The study of the UV spectrum originating from the expanding ejecta provides important information about the evolution of the outburst. In this paper we studied a number of emission lines with a wide range of ionization potentials along with the short wavelength ultraviolet continuum. We studied the Fe II 1588 Å emission line, the C II 1336 Å resonance doublet, the O I 1306 Å collisionally excited resonance triplet pumped by Hydrogen Lyman β, the Al III 1854 Å line, the NV 1240 Å resonance line and the [Ne V] 1575 Å forbidden emission line. The time evolution curves for all the studied emission lines are

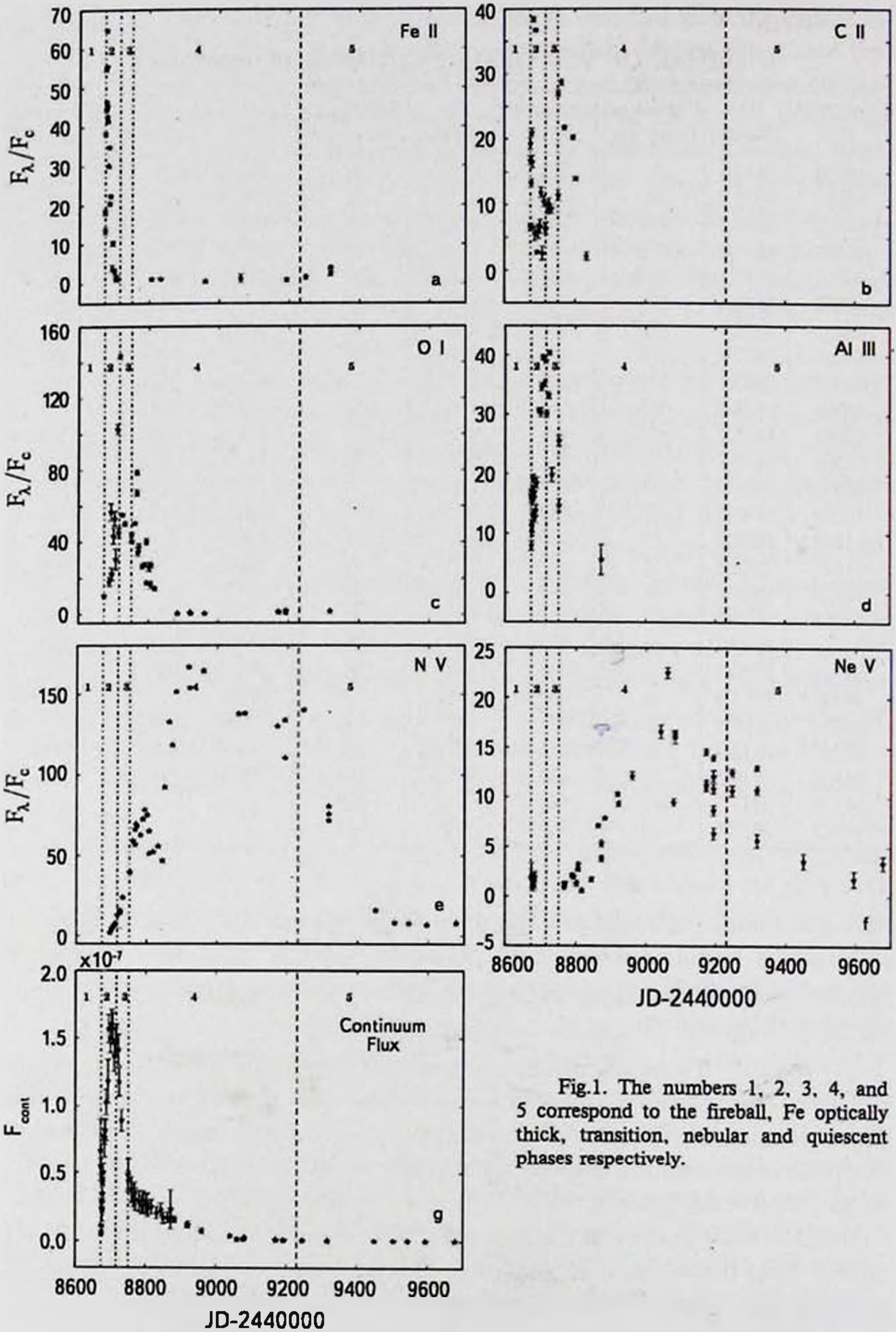

Fig.1. The numbers 1, 2, 3, 4, and 5 correspond to the fireball, Fe optically thick, transition, nebular and quiescent phases respectively.

shown in Fig.1. We calculated the ultraviolet luminosity of the emitting regions using the equation

$$L_\lambda = 4\pi F_\lambda d^2 \quad \mathrm{erg\ s^{-1}} \tag{1}$$

where F_λ is the integrated flux corrected for interstellar extinction using the equation

$$F = F_0 10^{0.4X(\lambda)E(B-V)} \quad \mathrm{erg\ cm^{-2}\ s^{-1}\ \AA^{-1}} \tag{2}$$

where F_0 is the observed unnormalized flux and $X(\lambda)$ is the fitted UV interstellar extinction function of Seaton [16].

We assumed that V1974 Cyg has reached quiescent state at about JD 2449230 nearly 560 days after the discovery (the dashed line in Fig.1). This is consistent with the stopping of the hydrogen burning according to the model of Hachisu & Kato [13]. We used the ultraviolet luminosity after this date to calculate the mass accretion rate on the white dwarf $\dot{M}_{acc}$ using

$$\dot{M}_{acc} = \frac{2L_{acc}R_{WD}}{GM_{WD}} M_\odot \ \mathrm{yr^{-1}} \tag{3}$$

where M_{WD} is the white dwarf mass taken as $1.05\,M_\odot$ [13], G is the universal gravitational constant, and R_{WD} is the white dwarf's radius calculated using

$$R_{WD} = 0.78\times10^9\left[\left(\frac{1.44\,M_\odot}{M_{WD}}\right)^{2/3} - \left(\frac{M_{WD}}{1.44\,M_\odot}\right)^{2/3}\right]^{1/2} \ (\mathrm{cm}) \tag{4}$$

from Nauenberg [17] and it was found to be $0.0073\,R_\odot$.

4. *Discussion*. The evolution of different line fluxes relative to the continuum (F_λ/F_c), show different phases of the outburst. The early spectrum of V1974 belongs to the permitted Fe II "P_{Fe}" class of Williams [18], where the spectrum originates from optically thick wind ejected by the white dwarf [1,19,20]. The Fe II 1588 Å line was the first line to reach maximum at JD 2448678 during the iron curtain phase of the outburst, where the cooling of the ejecta leads to the recombination of the iron peak elements. During this phase most of the remaining emission lines have low fluxes since they are blanketed by the iron curtain. The second line to peak was the C II 1336 Å line at JD 2448682. By the time this recombination line reaches maximum, the iron curtain is being lifted and the ionization is enhanced due to the retreat of the pseudo-photosphere. The iron curtain was completely lifted when the O I 1304 Å line reached maximum at JD 2448717 which is consistent with the evolution of this line in Cassatella et al. [21], the maximum of this line marks iron optically thick phase (both the iron curtain and lifting the iron curtain phases). The maximum of this line coincides with the time when the Fe II line drops to very low fluxes (see Fig.1a, c). The outburst then

enters the transition or pre-nebular phase and this is also clear from the optical observations of Rafanelli et al. [22]. The Al III 1854 Å line reached maximum at JD 2448725 and we can see from Fig.1d that this line can no longer be seen after JD 2448873 which means that it became completely ionized. The N V 1240 Å line reached maximum at JD 2448919 in the nebular phase. The last line to peak in our sample was the [Ne V] 1575 Å forbidden line at JD 2449061 in the nebular phase. At the times of maximum of the last two lines, the line opacity in the ejecta is now low and the ions are subject to harder radiation fields from the central white dwarf [7,20]. Tables 2-3 contain maximum, intermediate and minimum values for the studied lines. It can be seen that the studied lines reach maxima in order of increasing ionization potential showing that the outburst enters higher ionization conditions as time passes [23]. Note the disappearance of lower ionization line in the later phases of the outburst in Fig.1c, d and see Table 4. Cassatella et al. [24] studied the evolution of the integrated fluxes of four of the emission lines we studied (C II, Al III, O I and NV) during the first four stages

Table 2

V1974 Cyg Fe II, C II AND O I LINES

Value	Fe II	C II	O I
$(F_\lambda/F_c)_{max}$	64.7 ± 0.4	38.4 ± 0.3	143 ± 1
$F_{\lambda(max)}$ (erg cm^{-2} s^{-1} Å^{-1})	$3.2 \pm 0.1 \times 10^{-9}$	$4.5 \pm 0.1 \times 10^{-9}$	$3.14 \pm 0.02 \times 10^{-8}$
L_{max} (erg s^{-1})	$1.2 \pm 0.1 \times 10^{36}$	$1.7 \pm 0.1 \times 10^{36}$	$1.2 \pm 0.1 \times 10^{37}$
$(F_\lambda/F_c)_{mid}$	13.6 ± 0.8	10.5 ± 0.8	27 ± 1
$F_{\lambda(mid)}$ (erg cm^{-2} s^{-1} Å^{-1})	$6 \pm 2 \times 10^{-10}$	$6.8 \pm 0.3 \times 10^{-10}$	$9.7 \pm 0.2 \times 10^{-10}$
L_{mid} (erg s^{-1})	$2.4 \pm 0.8 \times 10^{35}$	$2.6 \pm 0.2 \times 10^{35}$	$3.7 \pm 0.3 \times 10^{35}$
$(F_\lambda/F_c)_{min}$	0.6 ± 0.4	2.1 ± 0.6	0.4 ± 0.2
$F_{\lambda(min)}$ (erg cm^{-2} s^{-1} Å^{-1})	$8 \pm 3 \times 10^{-13}$	$4.9 \pm 0.9 \times 10^{-12}$	$7 \pm 5 \times 10^{-13}$
L_{min} (erg s^{-1})	$3 \pm 1 \times 10^{32}$	$1.9 \pm 0.4 \times 10^{33}$	$3 \pm 2 \times 10^{32}$

Table 3

V1974 Cyg Al III, N V AND [Ne V] LINES

Value	Al III	N V	Ne V
$(F_\lambda/F_c)_{max}$	40.4 ± 0.4	166.4 ± 0.4	22.5 ± 0.5
$F_{\lambda(max)}$ (erg cm^{-2} s^{-1} Å^{-1})	$7.5 \pm 0.2 \times 10^{-9}$	$2.9 \pm 0.1 \times 10^{-9}$	$2.1 \pm 0.3 \times 10^{-10}$
L_{max} (erg s^{-1})	$2.9 \pm 0.2 \times 10^{36}$	$1.1 \pm 0.1 \times 10^{36}$	$8 \pm 1 \times 10^{34}$
$(F_\lambda/F_c)_{mid}$	16.9 ± 0.9	62.5 ± 0.5	6.4 ± 0.6
$F_{\lambda(mid)}$ (erg cm^{-2} s^{-1} Å^{-1})	$1.8 \pm 0.1 \times 10^{-9}$	$1.05 \pm 0.02 \times 10^{-9}$	$4.1 \pm 0.3 \times 10^{-11}$
L_{mid} (erg s^{-1})	$7.2 \pm 0.7 \times 10^{35}$	$4.1 \pm 0.3 \times 10^{35}$	$1.6 \pm 0.2 \times 10^{34}$
$(F_\lambda/F_c)_{min}$	6 ± 3	1.8 ± 0.2	0.6 ± 0.2
$F_{\lambda(min)}$ (erg cm^{-2} s^{-1} Å^{-1})	$1.1 \pm 0.1 \times 10^{-10}$	$2.3 \pm 0.3 \times 10^{-12}$	$4 \pm 2 \times 10^{-13}$
L_{min} (erg s^{-1})	$4.2 \pm 0.6 \times 10^{34}$	$9 \pm 1 \times 10^{32}$	$1.4 \pm 0.8 \times 10^{32}$

Table 4

TIMES OF MAXIMA OF DIFFERENT EMISSION LINES AND THEIR IONIZATION POTENTIALS

Line	T_{max} (JD-2440000)	Ionization Potential
Fe II	8678	7.90
C II	8682	11.26
O I	8717	13.60
Al III	8725	18.83
N V	8919	77.47
Ne V	9061	97.12

of the outburst and our evolutionary curves show a similar spectral behavior to theirs. Our calculated integrated fluxes agree with those calculated by Austin et al. [20] in the nebular phase and those obtained by Shore et al. [25] in the late nebular and quiescent phases. We have also calculated the evolution of the fitted continuum flux of the whole short wavelength range (Fig.1g). The continuum flux reached a maximum value of $\sim 1.6 \pm 0.1 \times 10^{-7}$ erg cm^{-2} s^{-1} at JD 2448703 $\pm$ 8 which is consistent with the time of maximum of the continuum flux at 1455 Å of Cassatella et al. [21]. This happens while the iron curtain is lifting where the pseudo-photosphere is receding and the emission from the hotter central regions is harder. The peak lags about 28 days after the visual maximum which shows the shift of the maximum emission towards shorter wavelengths [21,26]. The average luminosity of the studied lines is $\sim 6.5 \pm 0.6 \times 10^{35}$ erg s^{-1} and the average continuum luminosity is $\sim 1.5 \pm 0.2 \times 10^{37}$ erg s^{-1}.

The average expansion speed of nova outburst calculated from the velocities of the emission lines was ~2000 km s^{-1}. This, along with the adopted White dwarf mass make V1974 Cyg lie between models ONe1 and ONe2 of José & Hernanz [27]. The mass accretion rate is very low compared to the mass loss rate and the hydrogen burning rate in the early stages of the outburst and it only becomes significant in the quiescent phase of the nova [28]. Therefore we calculate the accretion rate in quiescence using equation (3) and we found a maximum value of $7.0 \pm 0.6 \times 10^{-9} M_{\odot}$ yr^{-1} from the NV line 574 days after the discovery of the outburst. The average accretion rate calculated from all lines was $6.6 \pm 0.6 \times 10^{-10} M_{\odot}$ yr^{-1}.

Austin et al. [20] assumed the ejected mass during the outburst $\sim 5 \times 10^{-5} M_{\odot}$. This value along with our calculated average accretion rate suggests a recurrence time of $\sim 0.76 \times 10^{5}$ yr.

The average temperature calculated using Stefan-Boltzmann law from the average continuum luminosity is $\sim 5.3 \times 10^{5}$ K which is close to the value calculated by Austin et al. [20]. It is slightly higher than the value of $\sim 3 \times 10^{5}$ K estimated by both Shore et al. [4] from the bolometric luminosity and Krautter et al. [29] by fitting the ROSAT X-ray observations during the nebular phase.

5. *Conclusion.* We used low resolution IUE spectra to investigate the spectral behavior of V1974 Cyg in both line and continuum. The temperature of the central white dwarf estimated from the fitted continuum is consistent with temperatures estimated by other authors.

The evolution of the spectral lines follows the linear relation between the time of maximum and the ionization potential of Cassatella et al. [23] although this relation was derived for CO novae while V1974 Cyg is an ONe nova.

The change in the ionization conditions such as opacity, temperature and density of the envelope leads to the variation of F_λ/F_c for different lines during different phases of the outburst.

The time of decline of continuum evolution curve is consistent with the time when hydrogen burning ends according to the model of Hachisu & Kato [13].

The average ejection velocity and adopted white dwarf mass suggest that V1974 Cyg lies between ONe1 and ONe2 classical nova models of José & Hernanz [27].

The evolutionary sequence described in Cassatella et al. [23] can be applied to V1974 Cyg adding the "Iron Curtain" phase before the initial phase.

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[1] Stellar Astronomy Lab, Astronomy Department, National Research Institute of Astronomy and Geophysics, 11421 Helwan, Cairo, Egypt,
e-mail: gamal.hamed@nriag.sci.eg mrsanad1@yahoo.com essam60@yahoo.com
[2] Department of Astronomy, Space Science and Meteorology, Cairo University, 12613 Giza, Egypt, e-mail: shahinazmostafa15@yahoo.com

ЭВОЛЮЦИЯ УЛЬТРАФИОЛЕТОВОГО СПЕКТРА V1974 Cyg НА IUE СПЕКТРАХ НИЗКОГО РАЗРЕШЕНИЯ

Г.М.ХАМЕД[1], М.Р.САНАД[1], А.ЭССАМ[1], Ш.ЮСЕФ[2]

Используя коротковолновые спектры IUE низкого спектрального разрешения, исследована спектральная эволюция некоторых нормированных эмиссионных линий ультрафиолетового диапазона на разных стадиях вспышки классической новой V1974 Cyg. Потоки эмиссионных линий рассчитаны и использованы для оценки ультрафиолетовой светимости излучающей области, а последняя использована для определения средней скорости аккреции массы во время фазы постновой. Оценены среднее значение яркости ультрафиолетового континуума $L_{cont} \sim 4.6 \pm 0.4 \times 10^{35}$ эрг с$^{-1}$ и средняя скорость аккреции массы $\dot{M}_{acc} \sim 6.6 \pm 0.6 \times 10^{-10} M_{\odot}$ г$^{-1}$. Используя значение светимости в континууме, для оценки температуры центрального белого карлика найдено среднее значение $\sim 3 \times 10^5$ K. Спектральное поведение объясняется изменением непрозрачности, температуры и плотности выбросов в разных фазах вспышки. Полученные результаты согласуются с теоретическими моделями классических ONe новых.

Ключевые слова: *новые: катаклизмические переменные - звезды: V1974 Cyg - ультрафиолет: звезды - белые карлики*

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