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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Физикалық-математикалық сериясы» ғылыми журналының Web of Science-тің жаңаланған нусқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын усынады. ҚР ҰҒА Хабарлары. Химия және технология сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді химиялық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия физико-математическая» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Вклю-чение Известия НАН РК в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по химическим наукам для нашего сообщества.

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SPECTRAL AND PHOTOMETRIC STUDY OF SOME WOLF-RAYET STARS

Abstract: Massive stars of spectral class O, leaving the Main Sequence (MS), are capable to lose their hydrogen envelopes. The remaining core begins to shrink, starting a sequence of nuclear reactions, the products of which are heavy elements C, N and O. The WR stage is an intermediate stage in the evolutionary path of massive stars to their final state: a neutron star or a black hole.

WR stars play an important role in evolution: firstly, they enrich the interstellar medium with heavy elements, and secondly, they are considered as progenitors of supernovae and as possible sources of X-ray flares.

This article presents preliminary results of observations of the group of WR stars. The spectra were obtained for three WC-type stars: WR 4, WR5, and WR154, and two WN-type stars: WR2 and WR3. On the basis of observational data, the absolute fluxes in the emission lines were obtained, the equivalent widths and half-widths of their profiles were determined. Comparison of our results for WR4, obtained over 2 nights, shows that in January 2021 the absolute fluxes in the emission lines decreased by 20% compared to the data of December 2020. Comparison with the data obtained in 1983-1984 did not reveal serious discrepancies in the results for WR4, but our values of the equivalent widths for WR5 turned out to be half as much. This may be due to an increase in the level of the continuum or due to decrease of the emission lines fluxes.

Photometric observations were carried out for four WR stars, with WR4 and WR5 observed over three nights. Comparison with the earlier data shows an increase in the brightness of objects over the past 20 years: by $0^m.2$ - $0^m.3$ for WR2 and WR5 and by $0^m.6$ -$0^m.8$ for WR4 and WR3.

So, at this stage, we have established the photometric variability of 4 WR stars: WR2, WR3, WR4, and WR5, as well as the spectral variability of at least two objects: WR4 and WR5.

Key words: emission objects, emission spectrum, B V R magnitudes, individual objects: WR2, WR3, WR4, WR5,WR136, WR139, WR154

Introduction. Wolf-Rayet stars ((hereafter WR) are the intermediate stage for massive stars on their evolutionary path to the final state: neutron star or black hole. They were assigned to a separate class due to their spectra with the broad (up to several thousand km/s) emission lines of He, N, C и O. These lines are forming in an envelope due to the powerful stellar wind of a central star. The deficit of hydrogen is another distinctive property of WR stars. These objects are considered to be formed from the O stars. They have the masses 10 - $25M_{\odot}$, and spend in the WR stage several million years [1]. WR stars are subdivided into three main subtypes: WN (nitrogen-rich), WC (carbon-rich) and WO (oxygen-rich), depending on the observed spectra.

Specifically, chemical composition of matter on the surface of the star and in its envelope depends on the type of nuclear reactions in the stellar interior. Thus WN and WC stars are the products of the CNO cycle (H-burning) and the triple-α (He-burning), respectively [2], and they enrich interstellar matter with these elements. It is believed that some WN stars (M = 20 - 30$M_{\odot}$) are formed from the luminous blue variables (hereafter LBVs). Just these stars have strong winds and hydrogen-poor atmospheres. It is known that some the most massive stars have WR spectra during their main-sequence phase, and young WR stars contain and display hydrogen in their atmospheres [3].

The formation and evolution of the WR envelope is determined by the stellar winds, sometimes with aid of Roche-lobe overflow in close binaries and/or episodic mass loss during stage.Giant ejection of LBVs stars may result the observed shell up to 10 $M_{\odot}$. The mechanism of such ejection is unknown, because light pressure is unable to do so [4].

WR stars are the main candidates as progenitors for core-collapse, supernovae (hereafter SNe) and the long gamma-ray bursts [5]. The study of WR stars has the great importance for our understanding of the properties of SNe and the resulting compact objects such as neutron stars or black holes.

It is very difficult to obtain the physical characteristics of an object before its SNe flash. To date, only in some cases it has been possible to associate the observed SNe outburst with its progenitor - the WR star.

Last year the spectral and photometric study of WR stars was began In Fesenkov Astrophysical Institute (FAI). The observation program included several WN and WC stars of medium brightness. It is planned to study the main characteristics and possible variations of the objects. This article presents preliminary observational results of our research.

Observations and data reduction

Spectral observations of WR stars are carried out with the diffraction spectrograph mounted the telescope AZT-8 (70cm). CCD camera SBIG STT-3200 (2184x1472, 6.8μ) is used as a detector. Some spectra of the objects were obtained with the Echelle spectrograph mounted the “Western” 1-meter Carl Zeiss Jena telescope of the Tien-Shan Astronomical Observatory (TShAO), the high altitude observational base of the FAI. During observations, the spectrograms of an objects and standards were obtained with a wide (7"- 10") entrance slit. Standard stars with a known energy distribution from [6] were used for the flux calibration Data reduction consists of subtracting the dark background and correction for atmospheric absorption.

Photometric observations of the objects were carried out with the «Eastern» 1-meter telescope located at the TShAO. The CCD camera Alta F16M (4096x4096, 9μ) of Apogee and a set of Johnson B V R filters were used. Several standard stars were chosen in the fields of the objects and were used for calibration. These stars, as a role, were located at small angular distances from the target, thus there is a negligible difference between atmospheric extinction for standards and object.

All instrumental BVRc magnitudes of the objects were transformed to the standard photometric system. The expressions for this procedure were obtained from photometric measurements of the stars from [7]. Obtained images were processed using the Bias, Dark and Flat files and the standard software package IRAF. The log of the observations is given in the Table1.

Table 1 – List of spectral and photometric observations

Dates of observations	Name of the object	Type of observations	Telescope
07.11.2020	WR136,WR139,WR154	Spectral	AZT-8
24.11.2020	HD 6327	Photometry	1-meter TShAO
05.12.2020	WR4, WR5	Photometry	1-meter TShAO
11.12.2020	HD 6327, HD 9974	Photometry	1-meter TShAO
16.12.2020	WR4	Spectral	AZT-8
03.01.2021	WR4,WR5	Spectral Photometry	AZT-8 1-meter TShAO
09.01.2021	WR4,WR5	Spectral	AZT-8
27.01.2021	WR4,WR5	Photometry	1-meter TShAO

Results of the spectral observations

WR4=HD 16523. This object is classified as a WC5 star [8]. It is surrounded by a gaseous envelope with the radius of 3.4 pc and is located at the distance of 4.9 kpc [9]. The main parameters of the star: T*=79000K and log L=5.3L⨀ were obtained in the paper [10]. The binary nature of WR4 was discussed in [11]. There are numerous emission lines of carbon (CII, CIII, CIV), helium (HeI, HeII) and oxygen (OII, OIII, OV, OVI) in the spectrum of WR4. Equivalent widths (EWs) of the emission lines in the spectrum of WR4 were determined in the paper [12]. The fragments of spectrogram of this star, obtained in 2020 in FAI, are presented in Figures 1. The most intensive lines are these of CIII, CIV. An analogous spectrum was obtained in the beginning of 2021.

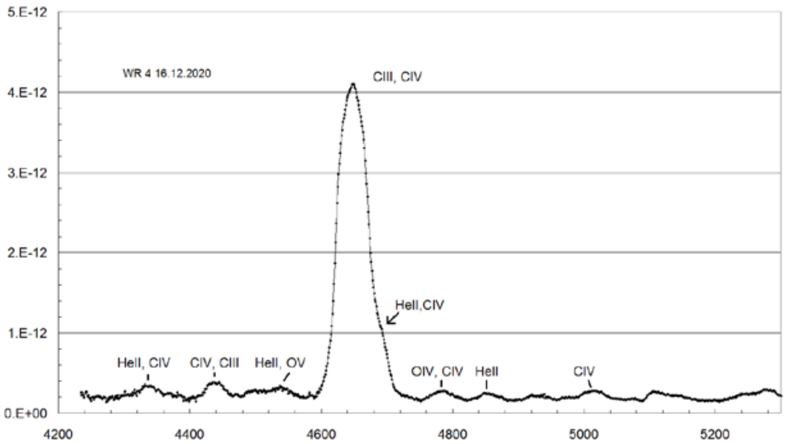

Figure 1 – The spectrum of WR4 in the “blue” range of the wavelengths. X axis -wavelengths in angstroms, Y axis - absolute fluxes in erg/cm^{2}sec

WR5=HD17638, is located at the distance of 1.4kpc. This object is classified as a single WC6 star [8]. Its dynamical age is evaluated to be 1.5 10^6 years [9]. Two fragments of spectrograms of this star, obtained in 2021, are presented in Figures 2,3.

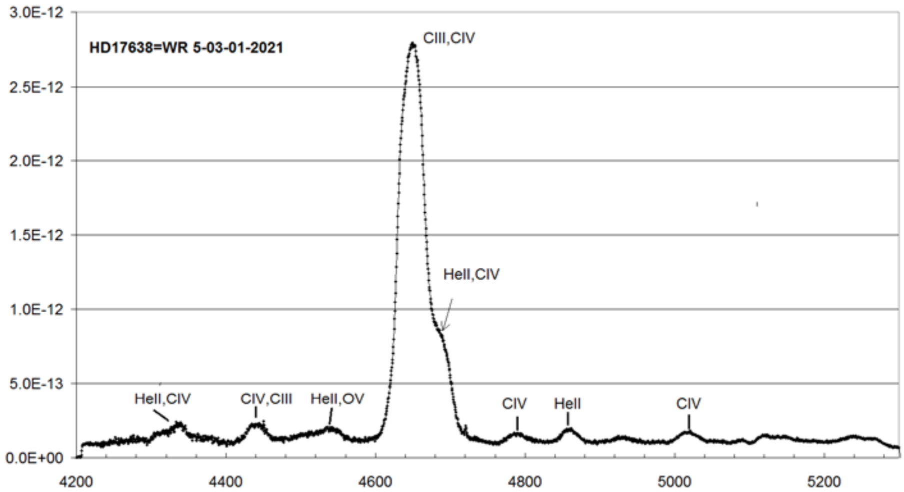

Figure 2 – The spectrum of WR5 in the “blue” range of the wavelengths.
Axes X and Y are the same as for Figure 1.

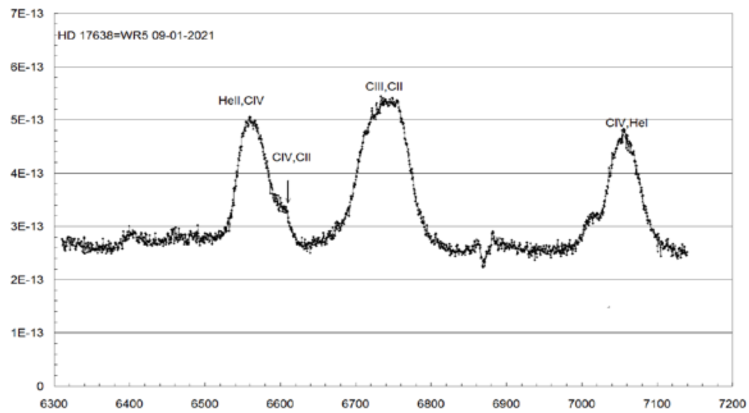

Figure 3 – The spectrum of WR5 in the “red” range of the wavelengths.
Axes X and Y are the same as for Figure 1.

WR154 =HD 213049 belongs to WC6 class. Information about its effective temperature and luminosity was compiled in [13]: T*=80000K, log L*=5.06L⊙. It is considered a single star, at least until significant RV variations were not detected [11].

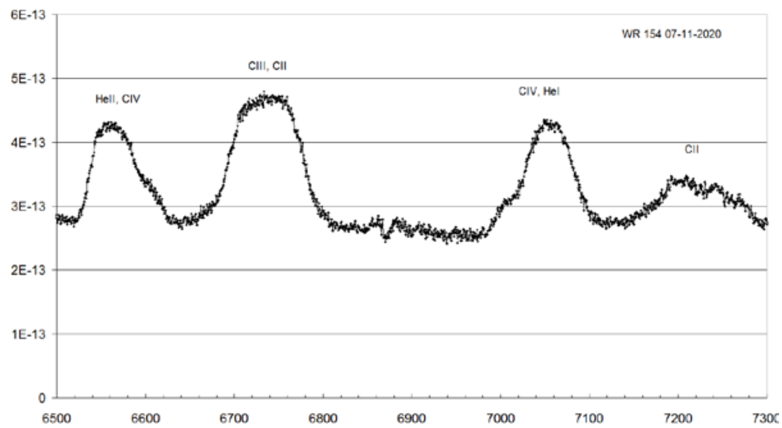

Figure 4 – The spectrum of WR154 in the “red” range of the wavelengths.
Axes X and Y are the same as for Figure 1.

The WR154 spectrum is similar to that of WR5, the CIII emission lines are stronger than the CIV and He lines. The main characteristics of the emission lines in the spectra of WR4, WR5 and WR154 are compiled in Table 2. These three objects belong to WC5 and WC6 sequences. Emission lines of CIII, 4650A and 6740A have the highest intensity in the blue and red fragments of the spectra.

Table 2- Fluxes and equivalent widths of the emission lines in the spectra of three WC stars

λ(Å)	Ions	Dates of observa-tions	16.12.2020 WR4	03.01.2021 WR4	1983-1984 WR4[12]	03.01.2021 09.01.2021 WR5	1983-1984 WR5[12]	07.11.2020 WR154
4340	HeII, CIV	$Fabs*10^{12}$	7.56±0.65	6.37±0.55		3.51±0.29		
		EW(A)	47	43	28	16	22	
		FWHM	35	39	29.9	41	22	
4440	CIV, CIII	$Fabs*10^{12}$	5.50±0.45	5.55±0.45		3.67±0.28		
		EW(A)	31	33	35	18	40	
		FWHM	39	33	31.4	36	28	

4515+ 4540	CIII HeII, OV	Fabs*10^12	7.7±0.65	5.75±0.45		4.83±0.35		
		EW(A)	32	34	22.4	24	35	
		FWHM	40	38	33.5	50	38	
4650+ 4686	CIII, CIV	Fabs*10^12	225±20	218±19		138±8.5		
		EW(A)	1394	1251	1549	690	1158	
		FWHM	52	54	82	40	62	
4780	CIV, OIV	Fabs*10^12	3.58±0.35	2.72±0.30		1.82±0.15		
		EW(A)	24	23	26	9.8	18	
		FWHM	37	35	33.6	35	30	
4860	HeII	Fabs*10^12	2.74±0.24	1.96±0.15		1.91±0.11		
		EW(A)	19	16	17	10	26	
		FWHM	34	32	30.6	27	27	
5017	CIV	Fabs*10^12	3.71±0.29	3.08±0.3		1.75±0.10		
		EW(A)	24	23	35	8.8	21	
		FWHM	35	37	41.3	32	31	
6560+ 6592	HeII, CIV	Fabs*10^11				1.10±0.10		0.91±0.12
		EW (A)				22	20	17
		FWHM				68	27	58
6744	CIII, CII	Fabs*10^11				2.12±0.20		1.76±1.44
		EW (A)				45	204	36
		FWHM				75	67	77
7060	CIV, HeI	Fabs*10^11				1.18±0.10		1.06±0.82
		EW (A)				25	44	21
		FWHM				45	51	60

There is almost no observational information about the spectra of researching objects. Only in the paper [12] equivalent widths and full width at half maximum (hereafter FWHM) of the emission lines in the spectra of several WR stars were determined, including WR4 and WR5. Comparing our results for WR4 with these data revealed discrepancies within the errors of observations. For WR5 our EWs are about half as much. This may be due to an increase in the level of the continuum or due to decrease of radiation fluxes in the lines.

WR136=HD 19163 is classified as a WN5 star. It is considered that it passed through an LBV phase before becoming a WR star. The strong wind swiped up the LBV ejecta into a ring nebula - NGC 6888 [9]. This nebula - consists of the inner filamentary zone (12´x 8´), which emits HI and [NII] lines, and the outer homogeneous sphere, emitting mainly in [OIII], 5007Å [14, 15]. Detailed study of WR136 and its nebula as far as the model approximation of its emission spectrum were carried out in the paper [16]. Fragments of the WR136 spectrum, obtained in FAI, are given in Figure 5.

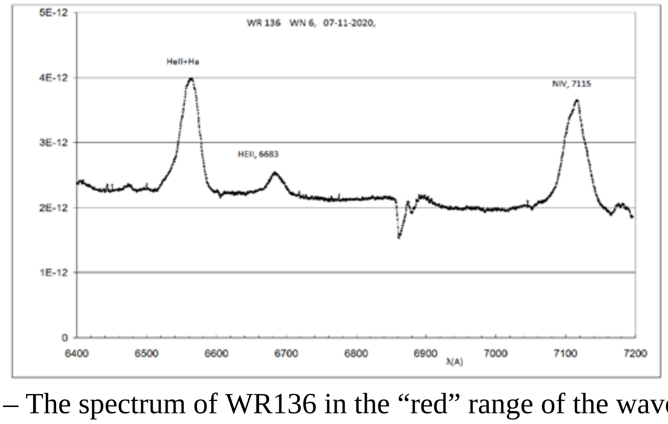

Figure 5 – The spectrum of WR136 in the “red” range of the wavelengths.

Axes X and Y are the same as for Figure 1.

WR139=HD 193576=V444 Cyg

This object is classified as an eclipsing binary WN5+O6. The inclination of the orbit (78º.7) gives a chance to measure the radial velocities for the both components. Emission lines are originated in the WR wind, and absorption – in the wind of the O star [17]. The orbital period of this system changes with time as such as the mass-loss rate. Masses of the components were derived by some authors, for instance, values M(O6)=28.4 ± 0.6 M⨀ and M(WR) - 12.4 ± 0.5 M⨀ were obtained by Eris[18].

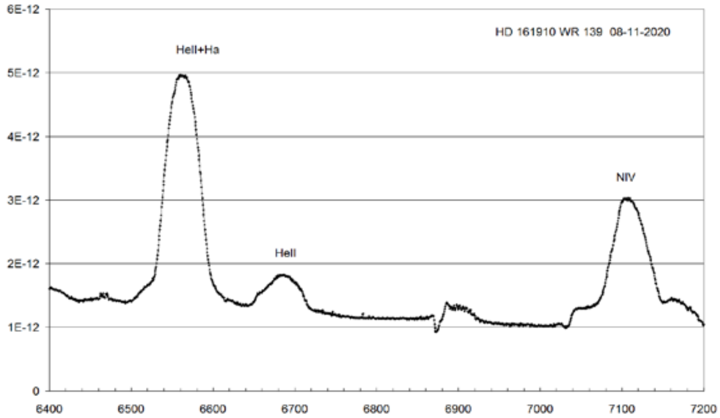

Figure 6 – The spectrum of WR139 in the “red” range of the wavelengths.
Axes X and Y are the same as for Figure 1.

Table 3- Fluxes and equivalent widths of the emission lines in the spectra of WR136 and WR139

λ(Å)	Ions	Dates of obs.	08.11.2020 WR136	08.11.2020 WR139
6560	HeII	Fabs*10^{11}	5.37±0.50	17.2±1.1
		EW(A)	13	68
		FWHM	30	47
6683	HeII	Fabs*10^{12}	1.17±0.35	2.31±0.18
		EW(A)	3.1	10
		FWHM	32	50
7115	NIV	Fabs*10^{12}	6.19±0.45	11.2±0.9
		EW(A)	17	56
		FWHM	35	50

Results of the photometric observations

Results obtained in FAI in the end of 2000 and in 2021, are given in Table 4. Data from CDS Strasbourg database are added. Unfortunately there is almost no information to compare our data with the earlier results for our objects.

Table 4- B V R magnitudes of four WR stars

Name of the object	Dates of observations	JD-2400000	B	V	R
WR4	05.12.2020	59189.11	9.783±0.039	9.837±0.097	9.889±0.050
	03.01.2021	59218.03	9.666±0.055	9.768±0.056	9.499±0.052
	27.01.2021	59242.13	9.712±0.052	9.808±0.055	9.930±0.042
WR4	From [19]		10.34±0.050	9.99±0.050	
WR5	05.12.2020	59189.12	10.589±0.042	10.528±0.093	9.705±0.020
	03.01.2021	59218.05	10.580±0.044	10.655±0.064	9.746±0.022

	27.01.2021	59242.15	10.611±0.045	10.657±0.063	9.763±0.023
WR5	From [21]		10.86±0.06	10.41±0.06	
WR2	24.11.2020	59178.09	11.066±0.089	11.195±0.023	10.957±0.028
	11.12.2020	59195.11	11.142±0.064	11.195±0.022	10.573±0.025
WR2	From[20]		11.49±0.05	11.33±0.07	
WR3	24.11.2020	59195.14	9.901±0.078	9.993±0.082	10.336±0.143
WR3	From [21]		10.71±0.064	10.69±0.064	

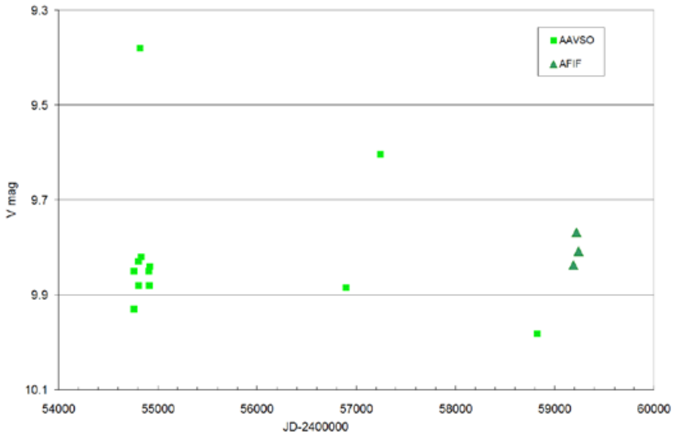

Figure 7- V magnitudes of WR4.

Additional data for WR4, in the V filter, taken from the American Association of Variable Stars Observers (AAVSO, see Figure 7), show a wide scatter of values ~ 0^m. 4. Quite detailed observations of this star were carried out in 2008; sample of points have a scatter of ~ $0^m.15$. Our results for WR4 and WR5 in filters B and V have the same scatter of values; in filter R, it is much larger. According to our data, in 2021 the WR5 brightness in the B filter is higher, and in the V filter - lower than the values from [21]. The maximum difference (~ $0^m.7$) between our values of brightness and the data from [21] was obtained for the star WR2.

Conclusions.

This article presents preliminary results of observations of the group of WR stars. Spectra are obtained for three WC and two WN stars. Emission lines of CIV and CIII are the dominant in the presented fragments of spectra of WC stars, and the lines of HeII are the most intensive in the WN spectra. Comparison of the spectral results obtained for WR4 shows that in January 2021 the absolute fluxes in the emission lines decreased by 20% compared to the data of December 2020. Comparing our results for WR4 with data, obtained in 1983-1984, revealed discrepancies within the errors of observations. For WR5 our EWs are twice lower. This may be due to an increase in the level of the continuum or due to decrease of fluxes in the emission lines.

Photometric observations were carried out for four WR stars, WR4 and WR5 were observed during three nights. The scatter of B and V values for different dates equals to $0^m.08 – 0^m.13$, and it is much larger in filter R,. Additional data for our objects from catalogs [19-21] are given in Table 4. Comparing with these earlier data reveals an increase of brightness of the objects: by $0^m.2$ - $0^m.3$ for WR2 and WR5 and $0^m.6$ -$0^m.8$ for WR4 and WR3.

So, at this stage, we have established the photometric variability of 4 WR stars:WR2,WR3,WR4 and WR5, and the spectral variability of at least two objects:WR4 and WR5.

This study will be continued, the further spectral and photometric observations are planned for a more complete understanding of the variability of the objects under study. For the WR stars, which are the progenitors of SNe Ib/c type, such characteristics of the stellar wind as its velocity and the mass loss power are of particular importance.

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WR ЖҰЛДЫЗДАР ТОБЫНЫҢ СПЕКТРЛІК ЖӘНЕ ФОТОМЕТРЛІК ЗЕРТТЕУЛЕРІ

Аннотация. О спектрлік класының массивті жұлдыздары негізгі тізбектен (БТ) кетерде өзерінің сутегі қабықшаларын жоғалтуы мүмкін. C, N, O ауыр элементтер өнімдері болып табылатын, ядролық реакциялардың келесі тізбегін орындауға қалған ядро сығыла бастайды. Массивті жұлдыздардың соңғы күйінің эволюциялық жолындағы WR аралық саты болып табылады: нейтрондық жұлдыздар немесе қара құрдым.

Эволюция кезінде WR жұлдыздары маңызды рөл атқарады: біріншіден, олар жұлдызаралық ортаны ауыр элементтермен қамтамасыз етеді, екіншіден, олар асқын жаңа жұлдыздардың негізін құрушы және мүмкін болатын рентген жарқ ету көзі ретінде қарастырылады.

Бұл мақалада WR жұлдыздар тобының алдын ала бақылау нәтижелері ұсынылған. WC жұлдыздар түріндегі үш жұлдыздың: WR 4, WR5 және WR154 және WN жұлдыздар түріндегі екі жұлдыздың: WR2 және WR3 спектрлері алынды. Бақылау мәліметтерінің негізінде эмиссиялық сызықтары сәулеленуінің абсолюттік ағыны, эквиваленттік ені және олардың профильдерінің жартылай ені анықталды. WR4 үшін 2 бақылау түрінің ішінде алынған нәтижені салыстыру барысында, 2021 қаңтардағы эмиссиялық сызықтар сәулеленуінің абсолюттік ағыны 2020 жылдың желтоқсанында алынған мәліметтермен салыстырғанда 20% төмендегенін көрсетті. 1983-1984 жылдары алынған мәліметтермен салыстырғанда WR4 үшін нәтижелер салмақты айырмашылық тудырмады, ал WR5 үшін біздің эквиваленттік енінің шамасы екі есе төмен болып шықты. Бұл эмиссиялық сызықтар сәулелену ағынының кемуімен немесе континуум деңгейінің өсуімен байланысты болуы мүмкін.

WR жұлдыздарының төртеуіне фотометрлік бақылаулар жүргізілді, сонымен қатар, WR4 және WR5 үш түн ішінде бақылау жүргізілді. Соңғы 20 жыл ішіндегі алдыңғы мәліметтерді осы мәліметтермен салыстырғанда объектілердің жарқырау шамасының артқандығын көрсетеді: WR2 және WR5 үшін $0^m.2$ - $0^m.3$ дейін және WR4 және WR3 үшін $0^m.6$ -0^m. 8 дейін артқан.

Сонымен, қазіргі кезде біз 4 WR жұлдыздарына фотометрлік айнымалылықты: WR2, WR3, WR4 және WR5, сонымен бірге, WR4 және WR5 объектілеріне спектрлік айнымалылықты анықтадық.

Түйін сөздер: эмиссиялық объектілер, Эмиссиялық спектрлер B V R жұлдызды шамалары, жеке объектілер: WR2, WR3, WR4, WR5, WR136, WR139, WR154

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СПЕКТРАЛЬНЫЕ И ФОТОМЕТРИЧЕСКИЕ ИССЛЕДОВАНИЯ ГРУППЫ WR ЗВЕЗД

Аннотация. Массивные звезды спектрального класса О, покидая главную Последовательность (ГП), способны терять свои водородные оболочки. Оставшееся ядро начинает сжиматься, запуская последовательность ядерных реакций, продуктами которых являются тяжелые элементы C, N O. Стадия WR является промежуточным этапом на эволюционном пути массивных звезд к их финальному состоянию: нейтронная звезда или черная дыра.

Звезды WR играют важную роль в эволюции: во-первых, они обогащают межзвездную среду тяжелыми элементами, во-вторых, они рассматриваются как предшественники сверхновых звезд и как возможные источники рентгеновских вспышек.

В данной статье представлены предварительные результаты наблюдений группы WR-звезд. Спектры получены для трех звезд типа WC: WR 4, WR5 и WR154 и двух звезд типа WN: WR2 и WR3. На базе наблюдательных данных получены абсолютные потоки излучения в эмиссионных линиях, определены эквивалентные ширины и полуширины их профилей. Сравнение наших результатов для WR4, полученных в течение 2-х ночей, показывает, что в январе 2021 г. абсолютные потоки в эмиссионных линиях снизились на 20% по сравнению с данными декабря 2020 г. Сопоставление с данными, полученными в 1983-1984 гг., не выявило серьезных расхождений результатов для WR4, а для WR5 наши значения эквивалентных ширин оказались вдвое меньше. Это может быть связано с увеличением уровня континуума или уменьшением потоков излучения в эмиссионных линиях.

Фотометрические наблюдения проводились для четырех звезд WR, при этом WR4 и WR5 наблюдались в течение трех ночей. Сравнение с этими, более ранними данными, показывает увеличение яркости объектов за последние 20 лет: на $0^m.2$ - $0^m.3$ для WR2 и WR5 и на $0^m.6$ -0^m. 8 для WR4 и WR3.

Итак, на данном этапе мы установили фотометрическую переменность 4-х звезд WR: WR2, WR3, WR4 и WR5, а также спектральную переменность как минимум двух объектов: WR4 и WR5.

Ключевые слова: эмиссионные объекты, эмиссионные спектры B V R звездные величины, индивидуальные объекты: WR2, WR3, WR4, WR5, WR136, WR139, WR154.

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