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REFINED ORBITAL PARAMETERS OF HD 193928[1]

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RESUMEN

Basados en 123 nuevos espectros de alta resolución y en datos previos ya publicados, se obtuvieron un mejor periodo de P = 21.6878 ± 0.0001d y una nueva solución para la órbita de la estrella Wolf-Rayet HD 193928. Usando la nueva función de masa del sistema y considerando los resultados recientes de Marchenko et al. (1998a), se discute brevemente la clase espectral probable de la compañera y un valor mínimo para su masa.

ABSTRACT

Based on 123 high-resolution CCD spectra carried out in 40 nights and previously published data, a refined period P = 21.6878 ± 0.0001d and a new orbit solution for the Wolf-Rayet star HD 193928 were obtained. In light of the newly derived mass function of the system, and taking into consideration the recent results of Marchenko et al. (1998a), the probable spectral class and minimum mass of the companion are briefly discussed.

Key words: **BINARIES: SPECTROSCOPIC — STARS: INDIVIDUAL: HD 193928 — STARS: WOLF-RAYET**

1. INTRODUCTION

HD 193928 (= WR141, van der Hucht et al. 1981) is a faint Wolf-Rayet star from the nitrogen sequence, classified as WN6 and SB1 (van der Hucht et al. 1988). Hiltner (1945; hereafter H45) has derived the first orbital parameters of the system measuring radial velocity (RV) variations of N IV λ4058, N V λ4604, and He II λ4686 lines. More recently, Ganesh & Bappu (1968; hereafter GB68) have refined Hiltner's orbit, using his value of the period P = 21.64d and have found that the mass function of the binary is f(M) = 4.62 $M_{\odot}$. These authors reported that the systematic radial velocities (RV) of He II λ4686 differs significantly from that of N V λ4603.7 and that there is a phase shift between the RV curves of He II λ4686 and N IV λ4058. Based on 15 CCD spectra and polarization data and also using Hiltner's ephemeris, Grandchamps & Moffat (1991; hereafter GM91) derived an orbital inclination of the system i = 71.7° and concluded that the masses of the components should be $M_{\rm WR} = 23.8 \pm 8.6\ M_{\odot}$ and $M_{\rm O} = 22.9 \pm 3.3\ M_{\odot}$. GM91 measured the RV variations of N IV λ4058 and H9/He II λ3835 and showed that these lines vary in antiphase. An interesting fact is that the γ–components in this work also differ remarkably: from their Figure 1, it can be seen that N IV shows $\gamma = -130$ km s^{-1}, but H9/He II shows $-\gamma = +130$ km s^{-1}. The first published photometric observations of WR141 (Moffat & Shara 1986) unfortunately, were dominated by light variations in comparison stars. The authors found that WR141 "... *is almost certainly not an eclipsing system*". The second photometric paper (Lamontagne et al. 1996) also did not resolve the problem with the eclipses in HD 193928; therefore, the photometry "... *reveals no significant dip at phase 0.0*", being dominated by significant intrinsic noise. The period adopted in this paper is 21.62081 days (see their Table 1).

The situation regarding the orbital period became more complicated after the publication of the re-

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sults from the spectroscopic study of Eeenens (1996; P = 21.635 ± 0.002d) and the *HIPPARCOS* photometry of 141 O and Wolf-Rayet stars (Marchenko et al. 1998a). In the latter paper, WR141 is considered as a WN6 + O4–5 (i.e., SB2) system with newly obtained period P = 21.03 ± 0.44d, "... *which is significantly different from the spectroscopic period*" (Marchenko et al. 1998a).

At the time of submission of the present paper, Marchenko, Moffat, & Eenens (1998b, hereafter M98) reported that the companion of the WR star in WR141 should be classified as O5. Using a specifically designed decomposition algorithm, the authors have restored the spectrum of the secondary and have estimated the masses of both components. Combining N IV λ4058 RV's from H45 and GB68 with their N IV λ4058 and He II λ4200 measurements, M98 refined the orbital parameters of WR141 and proposed a period P = 21.6895 ± 0.0003d. As one can see from the results section of the present paper, this independently obtained value of the period is very similar to ours, although it differs significantly according to the formal errors.

The fact is, that the estimates of the orbital period before M98 and this article (derived by H45, Lamontagne et al. (1996), Eenens (1996), and Marchenko et al. 1998a) give unacceptable RV curves with large phase displacements between different sets of spectral data. The determination of a more precise value of the period could provide a more coherent assessment of the spectral variability arising from orbital motion as opposed to other sources.

The aim of this paper was to refine the period and the other orbital parameters of HD 193928 using high-resolution CCD spectra and previously published data (except these of M98). More detailed analysis of the spectral and photometric variability will be published elsewhere. The observations and the reduction of the data are described in the following section (§ 2). The orbital elements, including a refined value of the period, as well as a short discussion, are compiled in § 3.

2. OBSERVATIONS AND REDUCTION

High-resolution spectroscopic observations were carried out at the 2-m RCC telescope of the Bulgarian National Astronomical Observatory during June 1996–March 1998. The Third camera of the coudè spectrograph and the 580 × 520 ISTA CCD array with a pixel size 24 × 18 μm were used. The Bausch & Lomb grating with 632 l/mm was used to reach a dispersion of 0.2 Å/pix and to cover a spectral range with more than 100 Å length centered on the He II λ5411 line. The reference spectrum was provided by a hollow-cathode Fe-Ar lamp. Flat-field frames were taken by using a tungsten lamp. The PC-based IPS software package (Smirnov et al. 1992) was used for data reduction. The procedure contains the usual steps of bias subtraction, flat-fielding, spectrum extraction and wavelength calibration. The spectra were normalized to the continuum by linear fitting of the line-free regions on both sides of the He II λ5411 emission line. The signal-to-noise (S/N) ratio reached in the individual spectra is typically around 100. In addition to the BNAO data we obtained some echelle spectra at the Observatorio Astronómico Nacional (OAN) in San Pedro Mártir (SPM)-México during September 1996 and August 1997. Wavelength calibration was done using a comparison He/Ar spectrum. The average signal-to-noise (S/N) ratio is around 100. The spectra were extracted from the images using the standard reduction packages of IRAF. To be comparable, all the spectroscopic data were re-binned to equal dispersion of 0.2 Å/pix in the wavelength range 5350–5480 Å, which gives an error in the RV's of less than 10 km s^{-1}. The central wavelength of the He II λ5411 line (λ_c) was obtained using two different approaches: a) By 'gravity center' defined as

$$\lambda_c = \frac{\sum_{j=1}^{N} \lambda_j F_j}{\sum_{j=1}^{N} F_j} \quad ,$$

where

$$F_j = \frac{F(\lambda_j)}{F_c} - 1 \quad ,$$

and $F(\lambda_j)$ is the flux at wavelength λ_j and F_c is the respective continuum flux.

b) By bisecting parabolic fits to the upper half of the emission line. Both methods gave identical RV's. The dates of the observations as well as the radial velocities are given in Table 1.

3. RESULTS

3.1. *The Period*

As it can be seen from the introduction, one of the most disputable orbital elements of WR141 is the period of the system. This can be easily explained by the lack (till now) of extended, homogeneous and high-precise spectroscopic data for this star.

One of the goals of this investigation was to check and refine the orbital period. Since the RV measurements of H45 and GB68 are separated in time by many cycles from each other and from our data, the period can be determined very accurately. It is well known that WR binaries sometimes show phase delays between the RV's of different emission and absorption lines.

In light of this fact, a reasonable question is: which lines should be used for radial velocities? All the lines at our disposal are more or less blended, e.g., N IV λ4058 has strong neighbours: He II/He I λ4026

TABLE 1

LIST OF THE MEASURED RADIAL VELOCITIES OF THE HE *II* λ5411[a]

HJD 2400000+	RV	HJD 2400000+	RV	HJD 2400000+	RV
50244.383	−76	50297.323	158	50330.559	−56
50244.395	−74	50298.322	213	50342.705	219
50270.535	9	50298.336	215	50342.715	215
50270.549	9	50298.351	213	50342.726	211
50270.564	11	50298.492	220	50343.708	223
50271.565	42	50298.506	219	50343.719	219
50271.580	39	50298.521	215	50343.730	220
50291.555	7	50299.280	232	50344.624	196
50291.560	12	50299.295	227	50344.634	207
50292.498	32	50301.371	218	50344.645	207
50292.512	32	50301.386	221	50345.633	170
50294.452	92	50302.308	196	50345.644	155
50294.466	94	50302.322	193	50345.655	162
50295.340	125	50302.337	182	50413.320	45
50295.355	122	50302.567	191	50413.341	57
50295.369	112	50302.581	188	50476.179	170
50295.384	122	50321.442	194	50476.196	161
50296.354	166	50321.456	195	50476.654	132
50296.368	157	50321.467	194	50476.668	144
50296.383	152	50325.279	113	50476.683	140
50296.398	157	50325.293	109	50476.687	135
50297.293	154	50330.530	−49	50565.570	56
50297.309	153	50330.541	−45	50565.584	53
50565.599	73	50650.318	146	50692.734	146
50565.608	55	50650.333	143	50692.745	166
50615.536	−32	50650.346	141	50692.756	133
50615.547	−31	50650.361	136	50716.287	110
50617.547	39	50689.746	243	50879.604	34
50617.557	39	50689.753	241	50879.618	45
50618.555	44	50689.761	242	50880.549	82
50618.566	50	50689.768	247	50880.560	86
50618.574	41	50689.776	233	50880.571	100
50643.566	173	50689.783	229	50880.581	87
50643.578	173	50690.731	229	50998.474	73
50643.585	173	50690.738	253	50998.489	69
50648.439	175	50690.746	234	50998.523	65
50648.447	172	50690.753	236	51001.422	−14
50648.468	175	50690.760	221	51001.436	−16
50649.389	170	50691.774	191	51001.450	−7
50649.410	163	50691.784	185	51002.475	−46
50649.425	157	50691.795	190	51002.495	−48

[a] In km s^{-1}.

and N III/He II λ4100; N V λλ4603, 4620 is a doublet with P Cyg absorption components, additionally blended by the N III λ4640 multiplet; the blue wing of He II λ4686 is contaminated by the N III λ4640 multiplet.

From this short overview it is clear that He II λ4686 has some advantages. In addition, for N IV λ4058, H45 wrote: "... *The line NIV λ4058 appears to vary appreciably in structure. The velocity-curve for this band is distorted, and this distortion is probably related to the variation in structure of the band*".

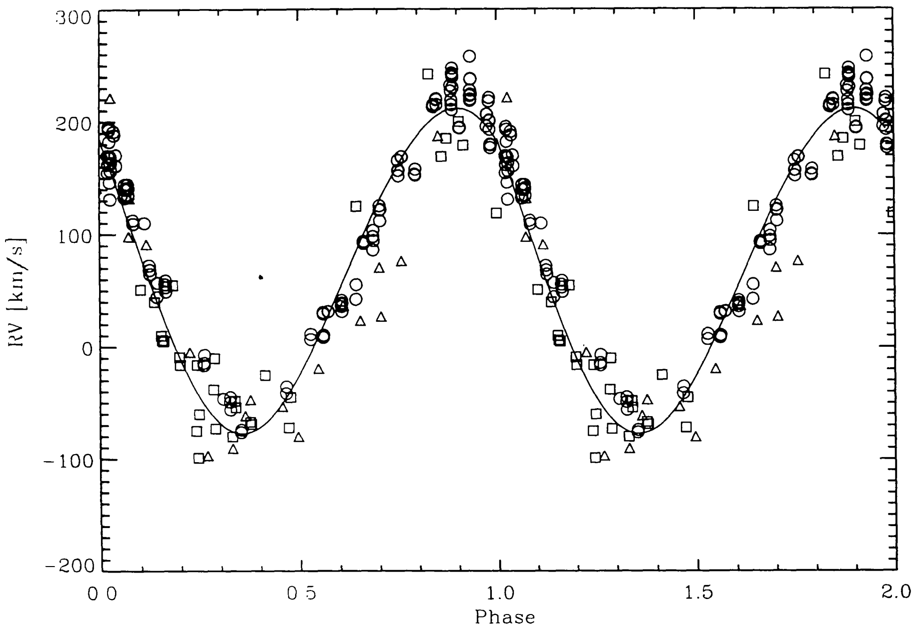

Fig. 1. Radial velocity variations of the He II λ4686 and He II λ5411 emission lines in the spectrum of WR141; the circles give He II λ5411 line velocities; the squares, He II λ4686 (H45); the triangles, He II λ4686 (GB68); the solid line represents the orbital motion defined by parameters of Table 2. Phase 0.0 corresponds to the time of the periastron passage T_0.

On the other hand, GB68 (our other source of data) reported that there is a phase shift of N IV λ4058 RVs with respect to those of the N V λλ4604, 4620 and He II λ4686 lines. The authors conclude: "... *It is difficult to explain the nature of this phase shift as seen in 4058 Å. It is likely that over the duration of the observations there has been activity on the star seen in NIV λ4058 causing such a displacement*". Finally, M98 claimed: "... *The NIV 4058 Å line, taken as a frame of reference for γ(WR), is notorious (cf. Smith & Willis 1994; Marchenko et al. 1996 and references therein) for the large negative displacements arising from formation of this line in the rapidly expanding, accelerating WR wind*".

Taking into account the aforementioned facts and that He II λ4686 and He II λ5411 vary simultaneously (which was tested on our echelle SPM spectra), we decided that the less erroneous approach is to use the He II λ4686 RVs in combination with He II λ5411 instead of N IV λ4058 + He II λ5411.

As a first step we adopted the approach described in Massey (1981) and applied to HD 186943 and HD 211853; therefore, we recomputed the times of conjunction T_γ (γ-crossing) for these three sets (i.e., ours, H45, and GB68) of data separately and looked for the period which gives an integer number of cycles between each couple of T_γ. The resulting value for the period is P = 21.6878 ± 0.0001. We have adopted this period as an initial estimate and left it as a free parameter during the iterative calculations of the orbital elements described in the following subsection. As can be seen from Table 2, this value remained unchanged after the computations.

3.2. *The Orbital Solution*

To compute the orbital parameters of WR141 we have used the program package BERT (described in Bertiau & Grobben 1968), which is based on the

TABLE 2

ORBITAL ELEMENTS AND DERIVED PARAMETERS OF WR141

Parameter	Value	
Period (days)	21.6878	± 0.0001
e	0.10	± 0.01
γ (km s^{-1})	76	± 1
K (km s^{-1})	137	± 2
T_0 (2450000+)	301.8	± 0.4
ω_0(°)	40	± 7
a sin i ($R_\odot$)	58	± 1
f (M) ($M_\odot$)	5.7	± 0.2
σ_{O-C} (km s^{-1})	13	...

methods of Schlesinger and Sterne. First we obtained the initial values of the elements using the graphical method of Lehman–Filhes applied to our data only. Combining all the spectral sets, the final parameters were calculated. Table 2 gives these final elements. Figure 1 presents the observed and calculated radial velocities for the emission lines He II λ4686 (from H45 and GB68) and He II λ5411 (this work). As one can see from Table 2 and from the respective solutions of H45 and GB68 the γ-axes as well as the semiamplitudes for the He II λ5411 and He II λ4686 practically coincide, while the estimate of the mass function differs from the previously published value.

It is well known that the mass function is a lower limit for the mass of the unseen companion. In the case when $M_{\rm O} \leq M_{\rm WR}$ (see M98)

$$M_{comp} \geq 4 * f(M) \quad ,$$

where M_{comp} is the mass of the secondary.

Then for the lower limit of the companion's mass we obtain 22.8 $M_{\odot}$, which is in good agreement with the results of M98 ($M_{\rm O}$ = (26–33) $M_{\odot}$).

The suggestion that the secondary could be a compact star (see Hamann, Koesterke, & Wessolowski 1993; Hamann et al. 1995, and Hamann & Koesterke 1998) should be questioned. On the other hand, since the presence of lines of the companion is not detected in our spectra, the question about its exact spectral class remains open. We can only suppose from our orbital solution that the other component could be normal O-star.

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