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WR 35a: A new double-lined spectroscopic binary[*]

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ABSTRACT

Aims. We present the first orbital solution for the Wolf-Rayet star, WR 35a, that was discovered by a spectroscopic monitoring of faint WN-type stars.
Methods. Spectral features of two different components were identified, and thus a method of disentangling the individual spectra of both components was applied. Radial velocities were determined for each component in the binary system.
Results. The orbital solution and component properties of the system were derived. We determined that WR 35a is composed of a WN6 star with a O8.5 V companion orbiting at a 41.90-day period.

Key words. binaries: spectroscopic – stars: individual: WR 35a – stars: Wolf-Rayet

1. Introduction

Multiplicity seems to be a widespread property of massive stars. There are many studies pointing in this direction: e.g., Sana et al. (2012) and Sana et al. (2013) and many references therein. The observational evidence leads to an intrinsic binary fraction greater than 50%.

Taking this observational fact into account, we are conducting a systematic spectroscopic monitoring campaign of galactic massive stars using both high- (OWN; Barbá et al. 2010) and low-resolution observations (Collado et al. 2013). The latter, only for faint WN-type stars, has resulted in the discovery of three double-lined binary systems (SB2), namely WR 62a, WR 68a, and WR 35a. SB2s are very important astrophysical objects since minimum stellar masses are derived from their orbital solution. Thus, they strongly contribute to our understanding of the evolutionary processes involved in such kind of stars.

WR 35a (=2MASS J11002434-5959357; V = 13.92) is a Wolf-Rayet star discovered by Shara et al. (1991) and classified as WN6. They were not able to detect absorption lines in the spectrum. No other analysis of this star was found in the available bibliography. In the following, we report the discovery of its binary nature, show the individual spectrum of each component, and provide the first orbital solution.

2. Observations and data analysis

The spectra used in this work were acquired between 1998 and 2013 with the 2.15 m telescope at Complejo Astronómico El Leoncito (CASLEO)[1], Argentina; with the 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO), Chile; and with the 8.1 m telescope at Gemini South Observatory[2], Chile. See Table 1 for a summary of the observations[3]. In all cases, comparison lamp spectra of He-Ne-Ar (or Cu-Ar) were observed immediately after or before, at the same telescope position as the stellar exposures. All spectra were processed with IRAF[4] routines. The GMOS package was employed with Gemini data.

2.1. Spectral disentangling

We applied an iterative method for disentangling the individual spectra and computing the radial velocities (RVs) of both components in spectroscopic binaries developed by González & Levato (2006). This technique consists in using the spectrum of one component to calculate the other. We used only our Gemini spectra since they constitute a homogeneous dataset,

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[1] Operated under agreement among CONICET and the Universities of La Plata, Córdoba, and San Juan, Argentina.

[2] Under Poor Weather proposals GS-2008B-Q-87 (PI: ANCh) and GS-2012B-Q-94 (PI: RG).

[3] Reduced spectra are available at the NOVA's Data Center via http://nova.conicet.gov.ar.

[4] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Details of the observations.

Obs. run UT	n	Sp. coverage [Å]	Observat.	Telesc. [m]	Spectr.[a]	Grating [l mm^{-1}]	Dispersion [Å pix^{-1}]	Resolution[b]
Feb., 1998	1	3940–5600	CASLEO	2.15	REOSC	600	1.63	1000
Apr., 2000	3	3940–5600	CASLEO	2.15	REOSC	600	1.63	1000
Apr., 2001	1	3940–5600	CASLEO	2.15	REOSC	600	1.63	1000
Mar.–Apr., 2007	5	3650–6700	CTIO	4	R-C	632	1.01	1300
Apr., 2008	1	3650–6700	CTIO	4	R-C	632	1.01	1300
Mar., 2009	1	4030–5590	CASLEO	2.15	REOSC	600	1.63	1000
Mar.–Jun., 2009	3	4120–6930	Gemini	8.1	GMOS	B600	0.92	1500
May, 2009	1	4470–5920	Gemini	8.1	GMOS	B1200	0.48	3000
Apr., 2010	3	4040–5700	CASLEO	2.15	REOSC	600	1.63	1000
Apr., 2011	2	3930–5600	CASLEO	2.15	REOSC	600	1.63	1000
Jan.–Feb., 2013	7	3920–6730	Gemini	8.1	GMOS	B600	0.92	1400
May, 2013	1	4030–5590	CASLEO	2.15	REOSC	600	1.63	1000

Notes. (n): Number of spectra obtained per run. [a] Details of the spectrographs can be found in the User's Manuals of the respective Observatories. [b] The spectral resolutions ($R = \lambda/\Delta\lambda$) were measured using $\Delta\lambda$ as the FWHM of the calibration lamp emission lines.

which sample the orbital phases and present good signal-to-noise ratios very well.

The method needs initial values of RVs to shift the spectra to a common velocity and to average them accordingly. Thus, we measured the He II λ4686 emission line to represent the WN orbital motion and the He I λ4471 absorption line to depict the secondary motion. The first step consists in shifting the input spectra by the WN's RVs and averaging them. It is thus expected that the secondary spectral features were diluted along the averaged spectrum. Then, all of the composite spectra are subtracted by this almost-pure WN spectrum (RV accordingly corrected), and the remaining spectra should be the secondary ones. These templates, which represent the individual spectra of both components, are then subtracted to each composite spectrum (paying attention to the respective RVs). The respective, almost-pure, individual spectra are cross-correlated (using FXCOR/IRAF) with the templates, and new RV are determined. These RVs are used again to calculate the new templates and repeat the cross-correlations. After several iterations, the templates and the RVs converge, and no improvements are obtained. Then, we used those templates to measure the RVs of the remaining spectra in the sample.

To calculate the templates, the spectral ranges used for the cross-correlation were $\lambda\lambda$4660−4710 for the WN component and $\lambda\lambda$4460−4485, 4532−4550, 4910−4930, 5005−5020, and 5400−5425 for the secondary component. The RVs of each emission line of the WN component were determined using an appropiate spectral range including the line.

3. Results and discussion

3.1. The individual spectra of both components

WR 35a presents a composite spectrum of absorption and emission lines, not noted by Shara et al. (1991). As proved below, the absorption lines move in opposite directions to the emission lines, so they belong to a secondary component. We therefore applied a disentangling method (see Sect. 2.1) to separate the individual spectra and classify them. Both spectra are shown in Fig. 1.

The WN spectrum was already classified as WN6 by Shara et al. (1991) and later reclassified as WN6h by Shara et al. (1999). We agree with the later classification.

Gemini/GMOS capability was invaluable for obtaining a high-quality spectrum of the secondary component by means of the disentangling process. This spectrum shows absorption lines that we identified as He I λ4026, 4387, 4471, 4713, 4921, 5015, and 5875, He II λ4200, 4541, 4686, and 5411, C III λ4069, and 4650, and more marginally Mg II λ4481 and N III $\lambda\lambda$4511–15. We classified the secondary as O8.5 V through a visual comparison of the disentangled spectrum with those of the atlas of spectral standards published by Sota et al. (2011) using the MGB code (Maíz Apellániz et al. 2012).

In the spectrum of WR 35a, the interstellar diffuse bands at 4430 Å, 4500 Å, 4726 Å, 4760 Å, and 4775 Å, are visible among others, which indicates that the star is very reddened.

3.2. The orbital solution

As is well known in binary systems with components of Wolf-Rayet type, the emission lines present different orbital solutions. Thus, we measured the RVs of the N IV λ4058, He II λ4541, 4686, and 5411, N V λ4604, and N III λ4640 emission lines independently (shown in Table 2). We searched for periodicities in the RV variations, using the Marraco & Muzzio (1980) algorithm, and obtained a 41.9-day periodicity for all the measured features.

We determined the orbital elements of each emission line by means of the FOTEL code (Hadrava 2004) and proved that the emission lines present a similar orbital motion. In all cases, the periodicity resulted in almost the same value, thus we assumed a mean P = 41.898 days. The eccentricity was found to be almost negligible, so we adopted a value of zero in all calculations.

The orbital parameters with the period and eccentricity fixed are shown in Table 3, ordered by the bounding energy of each transition superior level (E_B; Striganov & Sventitskii 1968). The orbital solutions are depicted in Figs. 2–7.

From Table 3, it seems that the He II λ4686 emission line is phase-shifted with respect to the other emissions by 0.7–2 days (or between 0.02 and 0.05 of phase). This is also reported in other WN+OB binary systems (see, e.g., Collado et al. 2013) and is related to the fact that its formation region is not spherically symmetric; e.g., it could have additional components in the wind-wind collision region. The different systemic velocities (V_{WR}), except that of the He II λ4686, seem to be correlated to their respective bounding energies. This behavior is expected if the expanding WN atmosphere presents a negative temperature gradient outwards, and it is frequently observed in WN+OB systems (see, e.g., Niemelä 1973; Gamen 2004). The emission lines
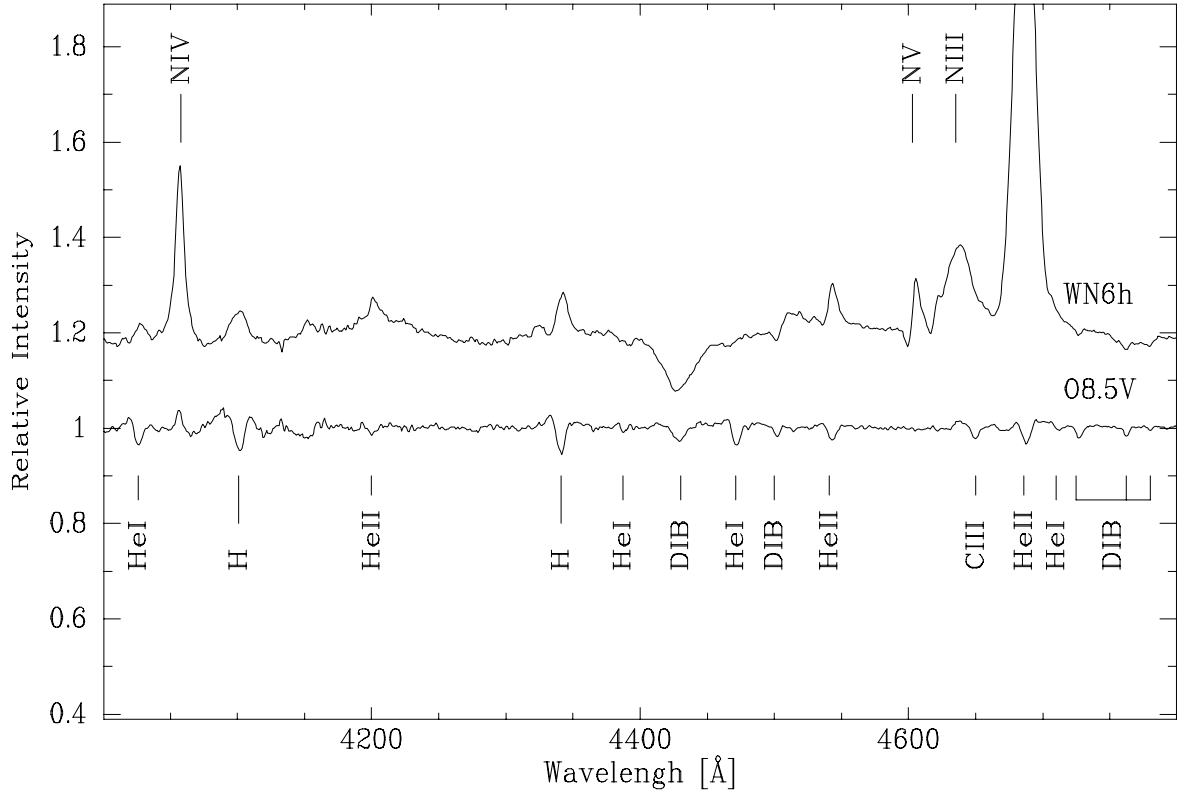
Fig. 1. Individual spectra of both components in WR 35a calculated by a disentangling method. The most important features are labeled below and above the respective spectra. Some diffuse interstellar bands (DIBs) are also identified.

Table 3. Circular orbital elements of WR 35a using different emission lines as representing the WR motion.

Parameter	N III $\lambda 4640$	He II $\lambda 4686$	N IV $\lambda 4058$	He II $\lambda 5411$	He II $\lambda 4541$	N V $\lambda 4606$
λ_0 [Å]	4640	4685.68	4057.76	5411.52	4541.59	4603.73
E_B [eV]	33.13	51.01	53.21	53.3	53.74	59.24
P [d]			41.898 ± 0.009			
T_{RVmax} [HJD-2 455 000]	704.4 ± 0.5	703.7 ± 0.4	705.7 ± 0.4	705.0 ± 0.4	705.1 ± 0.4	704.4 ± 0.4
V_{WR} [km s^{-1}]	-96	101	-19	134	133	170
V_O [km s^{-1}]	-15	-15	-15	-15	-15	-15
K_{WR} [km s^{-1}]	34 ± 11	110 ± 7	119 ± 9	97 ± 8	70 ± 10	99 ± 8
K_O [km s^{-1}]	93	92	92	93	92	93
q [M_O/M_{WR}]	0.37 ± 0.06	1.2 ± 0.2	1.3 ± 0.2	1.1 ± 0.2	0.8 ± 0.2	1.1 ± 0.2
$a_{WR} \sin i$ [$R_\odot$]	28.1	91.0	98.8	80.5	58.1	81.9
$a_O \sin i$ [$R_\odot$]	77.0	76.2	75.8	76.9	76.8	77.0
$M_{WR} \sin^3 i$ [$M_\odot$]	6.5	16.3	17.7	14.6	10.7	14.9
$M_O \sin^3 i$ [$M_\odot$]	2.4	19.5	23.0	15.3	8.1	15.8

also have different amplitudes, so that the minimum masses derived are discrepant among them. However, it seems that the O component is more massive than the WN star. Then, the system is in an advanced evolutionary stage, where the originally more massive star has experienced high mass-loss rates and is currently the least massive one in the system.

3.3. About the distance to WR 35a

Bearing the above discussion in mind, we adopted the N V emission line as representing best the orbital motion of the WN component, and thus, the resulting minimum masses are 14.9 $M_\odot$ for the WN6h and 15.8 $M_\odot$ for the O8.5 V star. Assuming that

the absolute mass of a O8.5 V is $M = 18.8\ M_\odot$ (Martins et al. 2005), the orbital inclination is found to be about $i = 71°$, so the absolute mass of the WN should be ~17.8 $M_\odot$.

Considering the evolutionary tracks of Ekström et al. (2012) in a very simplified scenario, a Wolf-Rayet star with this mass is compatible with $M_{ini} \sim 32\ M_\odot$ of 5.4 Myr old (in the same sense, the O8.5 V star is compatible with $M_{ini} \sim 19\ M_\odot$ of the same age). On the other hand, Collado et al. (2010) have discovered an early-type star in the surroundings of WR 35a. They relate this star to the 2MASS source J11002436-6000004 (=NOMAD1 0300-0240954 =USNO-B1 0300-0210713) and classify it as O9 III. We reclassify this spectrum as O9.5 II. The criteria for O8.5- to B0-type stars in Sota et al. (2011) are
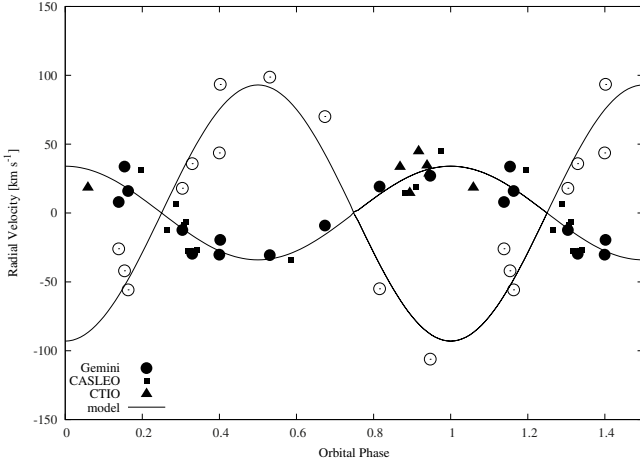
Fig. 2. Orbital solution of both components in WR 35a, using the N III λ4640 as representing the WN motion.
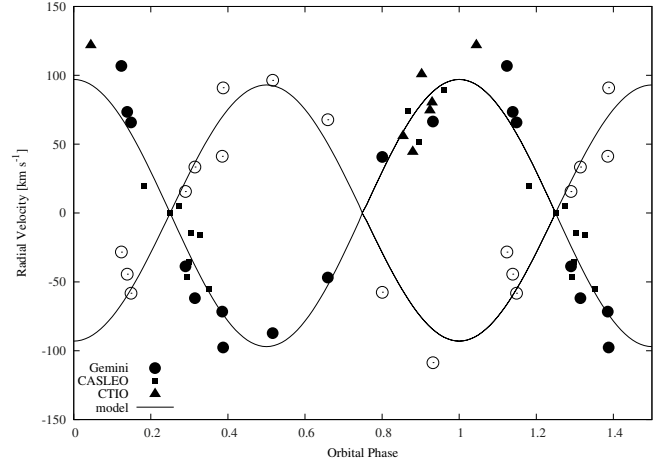

Fig. 5. Orbital solution of both components in WR 35a, using the He II λ5411 as representing the WN motion.
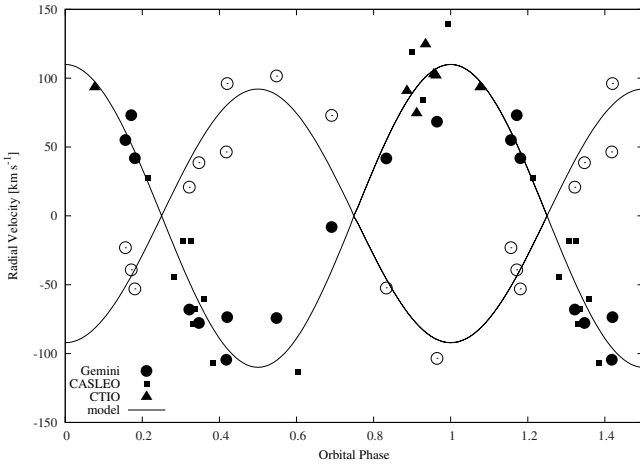

Fig. 3. Orbital solution of both components in WR 35a, using the He II λ4686 as representing the WN motion.
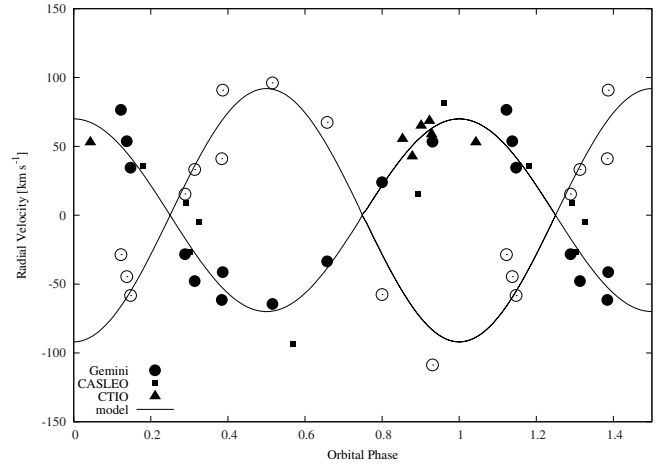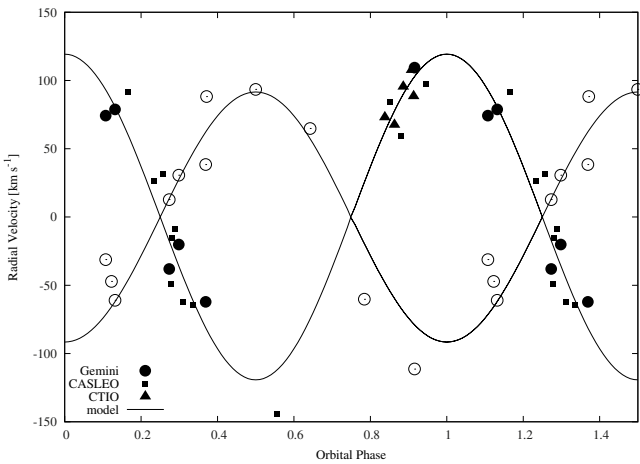

Fig. 6. Orbital solution of both components in WR 35a, using the He II λ4541 as representing the WN motion.

Fig. 4. Orbital solution of both components in WR 35a, using the N IV λ4058 as representing the WN motion.
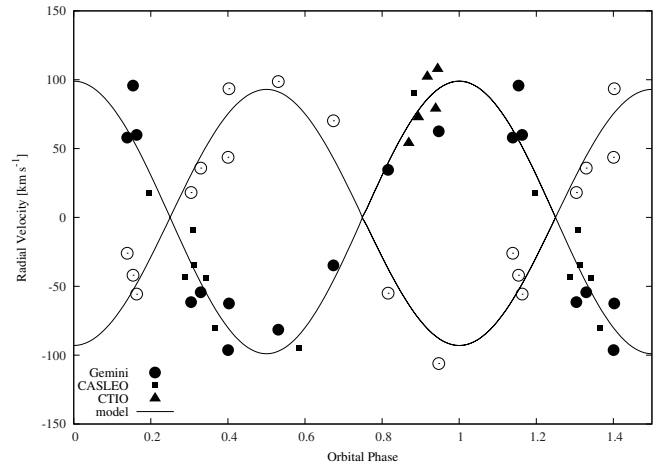

Fig. 7. Orbital solution of both components in WR 35a, using the N V λ4606 as representing the WN motion.

the He II λ4542/He I λ4388 and He II λ4200/He I λ4144 ratios, which in our case are much smaller than one. Also, the O9-O9.7 luminosity criteria He II λ4686/He I λ4713 and Si IV λ4089/ He I λ4026 ratios indicate a class III from the former, but a class Iab from the latter. Thus, the final spectral type was

decided by comparing the spectrum with the standard ones by means of the MGB code. Thus, this star could be assumed as having a mass of at least 21 $M_\odot$ (Martins et al. 2005), hence adding up to at least three stars with masses above 19 $M_\odot$ in a projected radius smaller than 0.50 arcmin.

We could assume that these stars have a common origin, thus forming an OB association or open cluster. A preliminary spectro-photometric distance can be determined to the 2MASS source J11002436-6000004 using the B and V magnitudes provided by Zacharias et al. (2004)[5] and assuming the absolute magnitude $M_V = -5.9$ (Walborn 1972), $B - V = -0.24$ (Wegner 1994), and the canonical ratio of total-to-selective extinction $R_V = 3.1$. We obtained an extreme distance of 21 Kpc using this R_V, but considering that this value seems to be very different towards the Carina arm (see Table 1 in Turner 2012), varying from the 3.1 to 5.5, this estimation may be as small as 8.5 Kpc. This discrepancy should be resolved with further photometric and spectroscopic analysis, to determine the actual R_V and thus find a more reliable distance. However, supposing equal interstellar extinction for both stars, the $m_V - M_V \sim 19$ of the O9.5 II star is rather similar to the WN6h+O8.5V obtained[6] value. Then, it is consistent with a common (unknown) distance.

4. Conclusions

We report the discovery of a new WN+O binary system, where the O8.5 V component is probably more massive than the WN6h star, thus indicating an advanced evolutionary state. Minimum masses, $M_{WR} \sin^3 i = 15\ M_\odot$ and $M_O \sin^3 i = 16\ M_\odot$, were determined assuming the N V $\lambda4606$ emission line represents the WN orbital motion, and the mean of some He I and He II absorption lines, the O component.

We discussed the distance and relationship of WR 35a and a O9.5 II neighboring star and proposed they may be at the same distance, hence forming an OB association or even an open cluster, which should be confirmed with follow-up observations.

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[5] NOMADS compiles the B magnitudes from Monet et al. (2003) and the V ones from the YB6 Catalog (USNO, unpublished).
[6] Assuming $M_V = -4.4$ for the O8.5 V (Walborn 1972), and $M_V = -4.1$ for the WN6 (van der Hucht 2001), $m_V - M_V \sim 18$ is obtained. If the $M_V = -7$ of a WN6h is chosen instead, $m_V - M_V \sim 20$ is obtained.

Table 2. Radial velocities measured in the spectra of WR 35a.

HJD-2 400 000	N IV λ4058	He II λ4541	N V λ4606	N III λ4640	He II λ4686	He II λ5411	abs.
50 868.772	–74	–86	–31	–18	–55		
51 653.659	61	–20		–12	–9	29	
51 654.637	8	2	19	–11	–2	27	
51 655.655	6		–17		–48	–12	
52 013.620	130	22		34	143	95	
54 190.594	83	57	79	40	123	135	
54 191.647	77	44	98	21	107	124	
54 192.615	105	66	128	51	157	180	
54 193.520	118	70	104	41	135	154	
54 193.749	98	60	133	35	134	160	
54 575.641		54		25	126	201	
54 916.580	162	43	81	47	87	63	
54 900.621		51	83	39	99	89	–62
54 972.490		–38	–33	–11	–17	–39	92
54 978.473		–7	14	10	49	1	64
54 998.588		81	145	53	130	121	–48
55 296.522	97			3	14	43	–32
55 297.524	102		20	22	41	49	–62
55 298.532	55		29	9	–20	8	
55 657.567	155		154	31	178	118	
55 661.485	168	88		61	198	133	
56 296.791	88	103	107	27	112	155	
56 297.824	93	61	109	35	99	114	
56 303.734	–24	–2	–13	7	–11	9	12
56 304.790	–6	–21	–6	–10	–21	–14	29
56 307.843	–48	–15	–14	0	–17	–50	87
56 307.746		–35	–48	–11	–48	–24	37
56 330.656	123	80	111	46	125	114	–113
56 429.595	21	16	54	7	41	–3	