Search for new Galactic Wolf–Rayet stars using Gaia DR3

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Aims

・This study aimed to utilize *Gaia* DR3 data to identify new Galactic WR stars.

Context

・The application of the **ELP-ELS algorithm** to the *Gaia* DR3 data, specifically low-resolution XP spectra, resulted in the identification of **565** sources as potential WR candidates that were published as part of the data release.
・Over half of them were already known as WR stars in the Milky Way and Magellanic Clouds.
・Our selection criteria, primarily based on 2MASS colors and pEW Hα measurements, produced a refined list of **59** strong candidates (~10% of the original sample).
・spectroscopically confirmed **33** (/37 <G=16mag) new Galactic WR stars, comprising 16 WN and 17 WC-type stars.
・detection of a possible new WR ring nebula surrounding WR-C-35, which we confirmed to be a WN8 star.

* ESP-ELS algorithm
: *Gaia Extended Stellar Parametrizer for Emission-Line Stars algorith*
: The classification model was trained on seven ELS categories: WC, WN, Be stars, Herbig Ae/Be stars, T Tauri stars, active M dwarfs, and PNe.

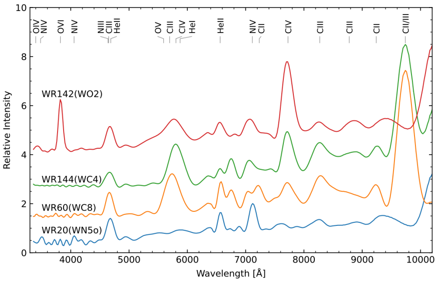
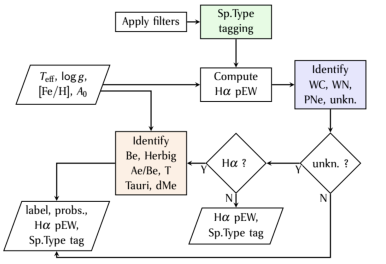


Fig. 1. Typical *Gaia* XP spectra of WR stars with main helium, nitrogen, carbon and oxygen lines marked.



Other Selection

- 676 known Population I WR stars from the **GWRC** (v1.29; May 2024) with the *Gaia* DR3 main catalog using a 1.5-arcsecond search radius.
  —-> identified **443** known WR stars with counterparts in *Gaia* DR3
- The ESP-ELS algorithm classified **229** of the 443 known Galactic WR stars in the *Gaia* DR3 main catalog as WR stars.
- The ESP-ELS algorithm failed to classify **214** of the 443 WR stars with counterparts in the Gaia DR3 main catalog as WR stars.

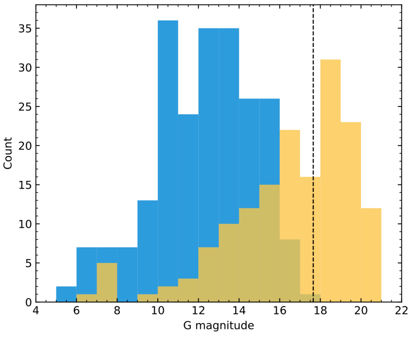
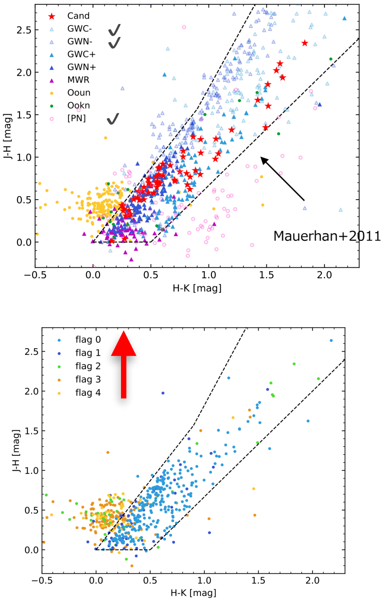
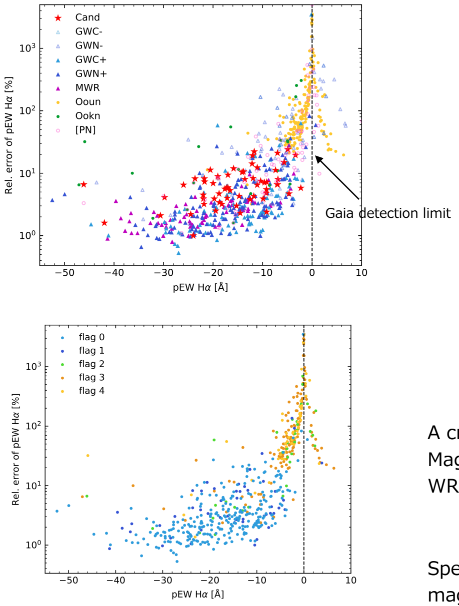


Fig. 2. Distribution of the *G* magnitudes of known Galactic WR stars. Stars included in the *Gaia* ESP-ELS analysis are shown in blue, while the objects not analyzed by the algorithm (for various reasons; see the text for details) are shown in yellow. The dashed black line represents the processing limit of the algorithm ($G < 17.65$ mag).



2MASS (NIR color-color)



EW H-alpha

Cross-match with SIMBAD

A crossmatch with the SIMBAD database revealed 16 known Magellanic WR stars and one additional Galactic WR star, WR111-6.

Spectroscopic follow-up

Spectroscopic observations of all bright candidates (G ≤ 16 mag) using facilities of the Southern Spectroscopic Project Observatory Team (2SPOT) consortium and through access to the Calern Observatory, affiliated with the Observatoire de la Côte d'Azur (OCA) were carried out.

Newly confirmed WC: C III λ5696 and C IV λ5806 lines
Newly confirmed WN: N IV λ4057, N V λ4604, and N III λ4640

All 37 of our bright candidates (G ≤ 16 mag) are confirmed the majority as WR stars. Of these, 33 are newly identified WR stars, while one source, WR-C-26, was already known as WR94.

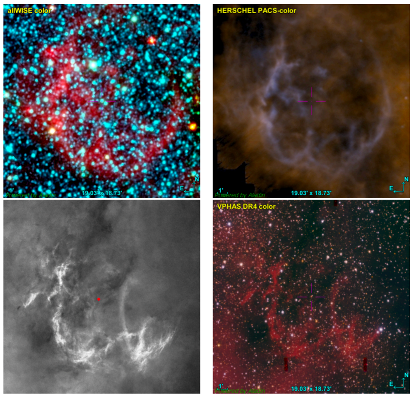


Fig. 14. Possible WR ring nebula of WR-C-35. **Upper row:** WISE color image (left) and Herschel PACS color image (right). **Bottom row:** Starless Hα image processed from SHS (left), VPHAS+ image from *u*, *g*, *r*, *i*, Hα bands (right).

This WR star lies near the center of a complex filamentary optical nebula, typical of material shaped by fast, hot stellar winds. Previously identified as an SNR under the designation G11.1-1.0, the nebula was recently reclassified as an HII region by Gao et al. (2019) and Dokara et al. (2021).

And more

・Suggestion the potential for future Galactic WR discoveries from Gaia low-dispersion spectra.
・This total includes three WR stars independently discovered by Marin et al. (2024). Of the observed candidates, only three were found not to be WR stars.

—> undiscovered Galactic WR stars remain to be found
— > necessary of/with other observations (ex; NIR-MIR)

Table 1. List of selected WR stars candidates.

Name	α_{2000} [h:m:s]	δ_{2000} [d:m:s]	l [°]	b [°]	G [mag]	pEWHα [nm]	SIMBAD ID	SIMBAD type[a]
WR-C-01	01:40:32.96	63:42:22.93	128.339	1.351	13.87	-2.39	Gaia DR2 512856654641310976	Em*
WR-C-02	06:14:34.49	18:28:28.27	192.365	0.533	11.04	-1.10	EM* AS 120	s*b/EB*
WR-C-03	06:27:28.07	04:54:58.03	205.816	-3.067	15.69	-0.91		
WR-C-04	08:26:21.63	-39:24:21.20	257.909	-0.729	16.37	-1.03		
WR-C-05	09:49:01.52	-55:28:32.99	279.037	-1.306	14.45	-0.98		
WR-C-06	10:15:21.03	-57:07:05.88	282.943	-0.432	15.22	-1.87	IRAS 10135-5652	LP?
WR-C-07	11:03:53.64	-61:03:05.83	290.287	-0.848	16.41	-0.96		
WR-C-08	11:24:36.53	-62:32:35.05	293.110	-1.339	16.75	-2.59	2MASS J11243656-6232350	LP?
WR-C-09	11:54:08.07	-62:04:48.14	296.279	0.049	16.28	-0.33		
WR-C-10	11:56:20.50	-62:34:37.81	296.636	-0.381	14.53	-1.24		
WR-C-11	12:56:45.51	-64:44:45.38	303.500	-1.880	14.63	-1.87	2MASS J12564553-6444453	LP?
WR-C-12	13:10:36.32	-63:12:27.29	305.090	-0.416	16.73	-0.73		
WR-C-13	13:29:11.16	-63:10:09.19	307.176	-0.609	17.12	-1.21		
WR-C-14	13:35:01.91	-61:58:38.42	308.028	0.462	13.27	-1.45	2MASS J13350193-6158384	LP?
WR-C-15	14:35:08.70	-61:14:02.54	315.079	-0.832	16.86	-1.99		
WR-C-16	15:16:59.19	-59:36:37.51	320.404	-1.770	15.98	-1.71		
WR-C-17	15:33:17.59	-49:48:14.22	327.798	5.090	16.40	-1.10		
WR-C-18	15:37:10.77	-56:13:18.48	324.521	-0.461	14.75	-1.65	IRAS 15332-5603	*
WR-C-19	15:37:41.30	-57:23:35.77	323.886	-1.448	16.23	-1.97		
WR-C-20	15:48:50.49	-55:11:20.18	326.453	-0.635	16.01	-2.17		
WR-C-21	16:48:01.37	-42:47:38.29	341.993	1.441	14.42	-1.52		
WR-C-22	16:49:41.87	-46:45:08.71	339.153	-1.332	16.28	-1.69		
WR-C-23	16:59:33.96	-47:05:36.67	339.948	-2.857	13.45	-0.69	2MASS J16593396-4705365	LP?
WR-C-24	17:12:41.98	-39:14:14.17	347.661	-0.031	14.96	-1.47		
WR-C-25	17:14:00.39	-40:30:42.08	346.776	-0.982	17.21	-2.05		
WR-C-26	17:33:07.83	-33:38:24.97	354.598	-0.248	11.32	-1.82	CD-33 12168B	*
WR-C-27	17:33:23.11	-33:43:52.46	354.551	-0.342	16.04	-1.38		
WR-C-28	17:33:41.28	-33:39:48.42	354.642	-0.358	10.83	-0.22	TYC 7380-64-1	*
WR-C-28	17:35:36.42	-33:55:57.72	354.632	-0.839	11.60	-0.91		
WR-C-30	17:41:27.51	-30:16:42.56	358.383	0.065	16.51	-1.20		
WR-C-31	17:59:19.86	-21:21:59.72	8.094	1.186	14.59	-4.19		
WR-C-32	18:04:52.43	-20:37:48.65	9.373	0.424	12.60	-1.94	THA 34-2	Em*/WR* [b]
WR-C-33	18:08:52.12	-23:55:27.12	6.946	-1.987	16.22	-2.17		
WR-C-34	18:09:48.33	-19:18:00.68	11.099	0.059	16.66	-1.58	2MASS J18094833-1918006	AB?
WR-C-35	18:14:12.97	-19:46:02.03	11.189	-1.076	13.73	-0.68	2MASS J18141297-1946019	LP?
WR-C-36	18:21:02.93	-12:27:45.65	18.398	0.945	14.44	-2.97	UCAC3 156-201972	PN
WR-C-37	18:27:10.29	-02:57:19.80	27.524	4.038	15.23	-2.19	2MASS J18271030-0257196	Y*?
WR-C-38	18:28:06.09	-10:05:01.46	21.309	0.529	14.66	-1.41		
WR-C-39	18:37:07.44	-04:25:48.79	27.357	1.155	14.87	-2.18		
WR-C-40	18:40:14.97	-05:03:20.12	27.159	0.176	12.75	-0.69	THA 14-54	Em*/WR* [b]
WR-C-41	18:40:35.23	-09:41:39.52	23.072	-2.021	15.75	-1.35		
WR-C-42	18:43:22.18	-01:03:37.30	31.068	1.311	15.11	-1.70		
WR-C-43	18:45:17.38	-02:48:13.10	29.736	0.088	14.97	-2.19		
WR-C-44	18:46:15.05	-05:42:21.13	27.263	-1.449	15.42	-1.73		
WR-C-45	18:53:05.40	-02:08:33.18	31.213	-1.344	17.20	-1.16		
WR-C-46	18:53:19.55	03:32:52.44	36.305	1.198	13.68	-0.56		
WR-C-47	19:02:21.70	08:47:09.20	41.992	1.590	15.97	-1.19		
WR-C-48	19:31:15.07	19:04:18.30	54.358	0.207	15.28	-1.17		
WR-C-49	19:32:13.42	-54:05:07.01	343.537	-27.498	17.58	-0.49		
WR-C-50	19:34:10.42	19:22:13.94	54.953	-0.253	13.93	-0.92	2MASS J19341042+1922141	LP?
WR-C-51	19:38:34.47	24:03:20.48	59.541	1.140	17.60	-1.90	2MASS J19383447+2403205	LP?
WR-C-52	19:52:40.81	23:29:33.90	60.672	-1.934	16.47	-1.76	2MASS J19524081+2329339	LP*
WR-C-53	20:09:08.72	36:38:00.92	73.711	1.980	16.76	-4.61	ZTF J200908.72+363801.0	LP*
WR-C-54	20:43:36.48	44:55:05.16	84.236	1.472	10.34	-0.46	LS III +44 21	EB*/WR* [b]
WR-C-55	20:57:40.95	46:59:44.99	87.394	0.902	15.44	-2.44		
WR-C-56	21:05:28.26	51:36:00.76	91.692	2.990	17.23	-2.36	ZTF J210528.26+513600.7	LP*
WR-C-57	21:19:47.42	53:22:25.00	94.481	2.622	15.76	-3.06		
WR-C-58	21:27:21.23	52:32:05.06	94.705	1.226	15.20	-0.70		
WR-C-59	22:09:50.11	60:22:33.67	104.210	3.518	15.20	-0.92		

Notes. [a]SIMBAD types correspond to the following classes: Em* - emission-line star; s*b - blue supergiant; EB* - eclipsing binary; LP*/LP? - long-period variable/candidate; * - star; WR* - WR star; AB? - asymptotic giant branch star candidate; PN - planetary nebula; Y*? - young stellar object candidate. [b]The type was updated to WR* after the first submission of this paper based on the classification by Marin et al. (2024); see the text for details.

Appendix B: Additional tables

Table B.1. Log of spectroscopic observations of WR stars candidates, together with their classification.

Object	Exposure time	Julian Date	Obs. Site	Subclass
WR-C-01	8 x 800 s	2460621.3142	Kermerrien	WN4
WR-C-02	3 x 180 s	2460613.6058	C2PU	Not WR
WR-C-03	2 x 1200 s	2460614.5568	C2PU	Not WR
WR-C-05	4 x 1200 s	2460618.8110	DSC	WC5
WR-C-06	6 x 1200 s	2460628.8177	DSC	Not WR
WR-C-10	6 x 1200 s	2460642.7981	DSC	WC5+abs
WR-C-11	4 x 1200 s	2460651.8212	DSC	WN5
WR-C-14	5 x 1200 s	2460535.5095	DSC	WC9
WR-C-16	6 x 1200 s	2460555.5337	DSC	WC8
WR-C-18	4 x 1200 s	2460549.5357	DSC	WC9d
WR-C-21	5 x 1200 s	2460544.5909	DSC	WC7
WR-C-23	4 x 1200 s	2460544.5182	DSC	WN8
WR-C-24	4 x 1200 s	2460554.5267	DSC	WC9d
WR-C-26	2 x 1200 s	2460548.5107	DSC	WN6 (WR94)
WR-C-28	3 x 1200 s	2460548.5512	DSC	WN6+abs
WR-C-29	4 x 1200 s	2460546.6710	DSC	WN7
WR-C-31	4 x 1200 s	2460547.6661	DSC	WC8
WR-C-32	3 x 1200 s	2460544.6543	DSC	WC9d
WR-C-35	2 x 1200 s	2460547.7168	DSC	WN8
WR-C-36	4 x 1200 s	2460549.5999	DSC	WN7h
WR-C-37	6 x 1200 s	2460559.5633	DSC	WC9
WR-C-38	4 x 1200 s	2460548.6088	DSC	WC9
WR-C-39	4 x 1200 s	2460546.6092	DSC	WN7-8
WR-C-40	3 x 1200 s	2460554.5815	DSC	WC9
WR-C-41	5 x 1200 s	2460559.6487	DSC	WN5-6
WR-C-42	7 x 1200 s	2460555.6315	DSC	WN6
WR-C-43	5 x 1200 s	2460548.6809	DSC	WC9d
WR-C-44	5 x 1200 s	2460554.6455	DSC	WN5-6
WR-C-46	5 x 1200 s	2460549.6716	DSC	WC8
WR-C-47	6 x 1200 s	2460561.0857	DSC	WC6
WR-C-48	4 x 1200 s	2460561.5978	DSC	WC7
WR-C-50	10 x 1200 s	2460549.4637	Kermerrien	WN5-6
WR-C-54	3 x 1200 s	2460626.2761	Cornillon	WN6+abs
WR-C-55	4 x 1200 s	2460614.4183	C2PU	WN3
WR-C-57	4 x 1200 s	2460615.3789	C2PU	WN/C
WR-C-58	3 x 1200 s	2460613.3071	C2PU	WC5
WR-C-59	7 x 1200 s	2460626.4319	Kermerrien	WN3

Appendix A: Optical spectra of our candidates

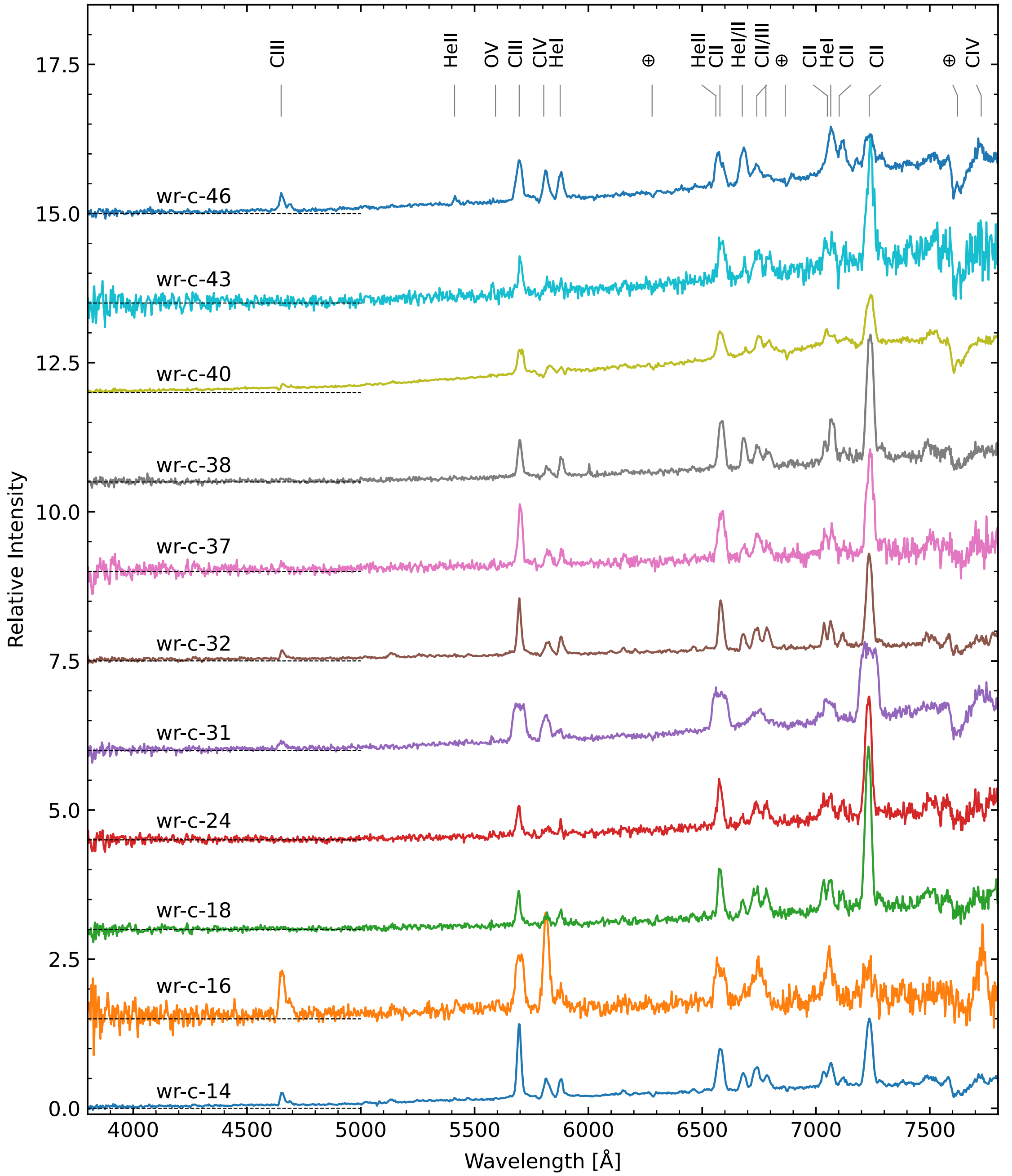


Fig. A.1. Spectra of newly discovered WC8 and WC9 stars. Spectra are dominated by C III emission. WR-C-31, WR-C-16 and WR-C-46 are the only WC8 stars in the sample, while the other stars belong to the WC9 subclass. The black dashed lines indicate the zero intensity scale of each spectrum. The position of the telluric absorption bands is marked with the symbol ⊕.

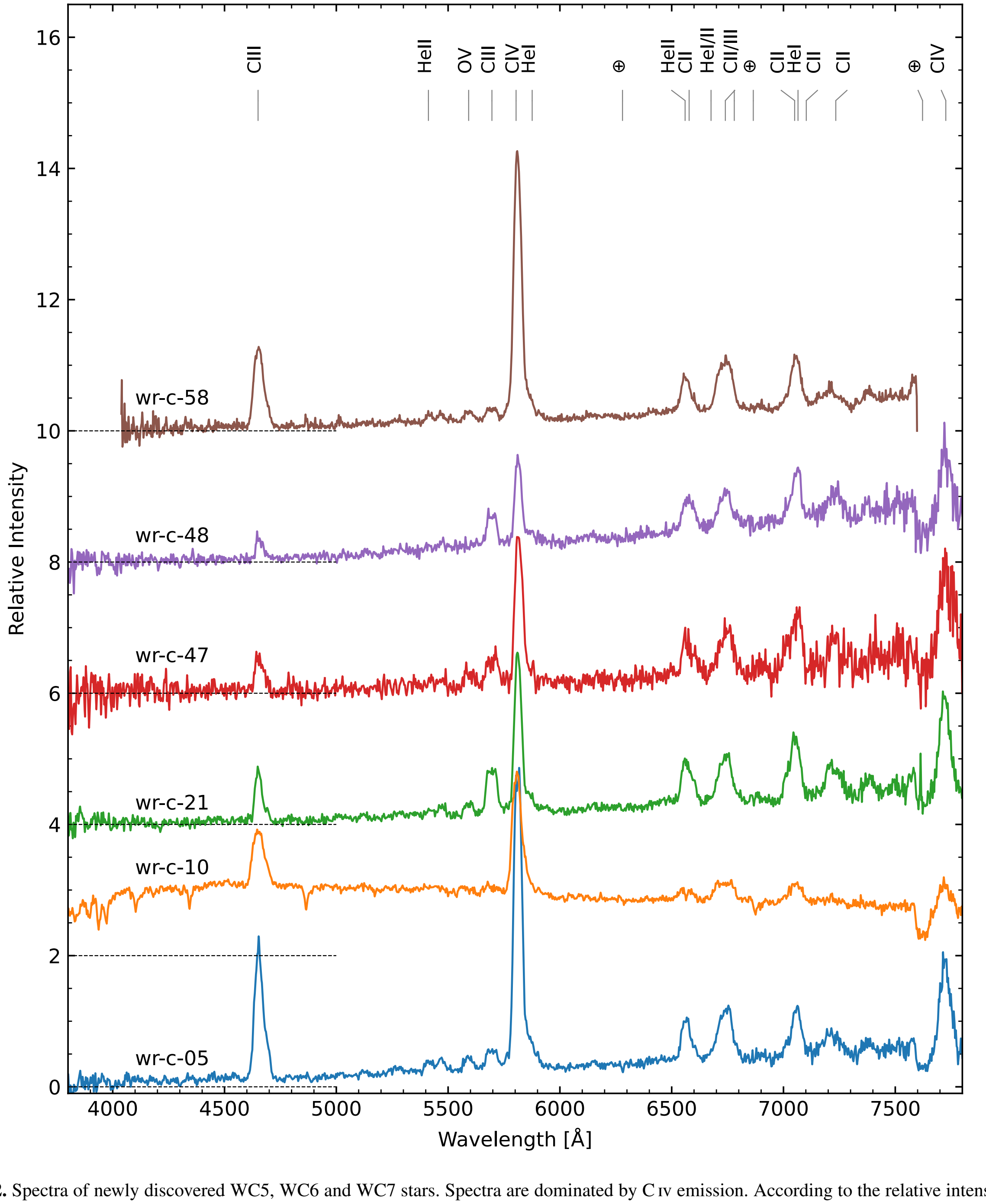


Fig. A.2. Spectra of newly discovered WC5, WC6 and WC7 stars. Spectra are dominated by C IV emission. According to the relative intensity of their O V and C III lines, WR-C-05, WR-C-10, and WR-C-58 belong to the WC5 subclass, WR-C-47 to WC6, while all other stars are WC7. The black dashed lines indicate the zero intensity scale of each spectrum. The position of the telluric absorption bands is marked with the symbol ⊕.

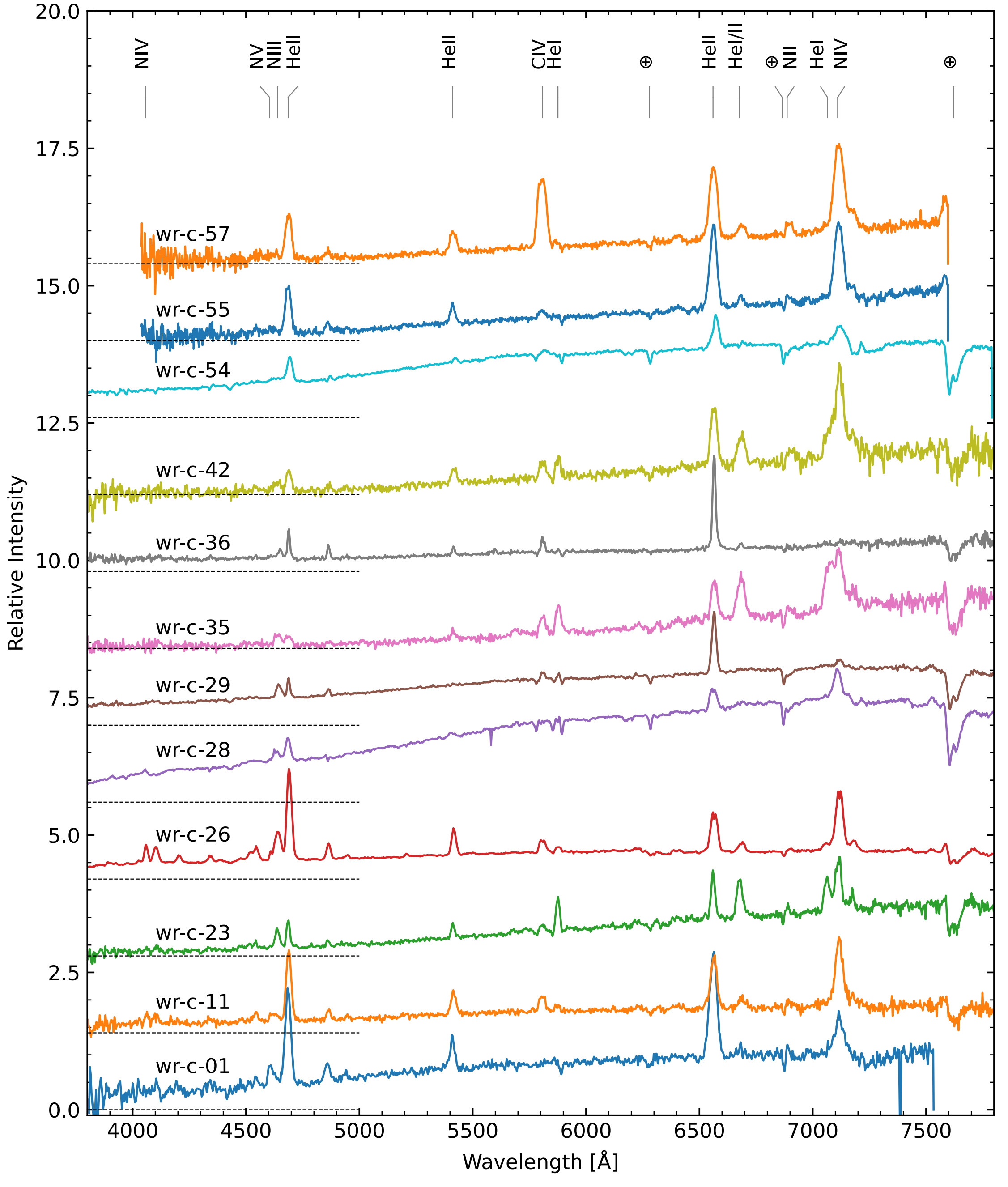


Fig. A.3. Spectra of newly discovered WN stars. WN/C: WR-C-57 for its unusually strong C IV λ5804 line, WN3: WR-C-55, WN4: WR-C-01, WN5: WR-C-11, WN6: WR-C-26 (already known as WR94, see text), WR-C-28, WR-C-42, WR-C-54, WN7: WR-C-29, WR-C-36, WN8: WR-C-23. The black dashed lines indicate the zero intensity scale of each spectrum. The position of the telluric absorption bands is marked with the symbol ⊕.

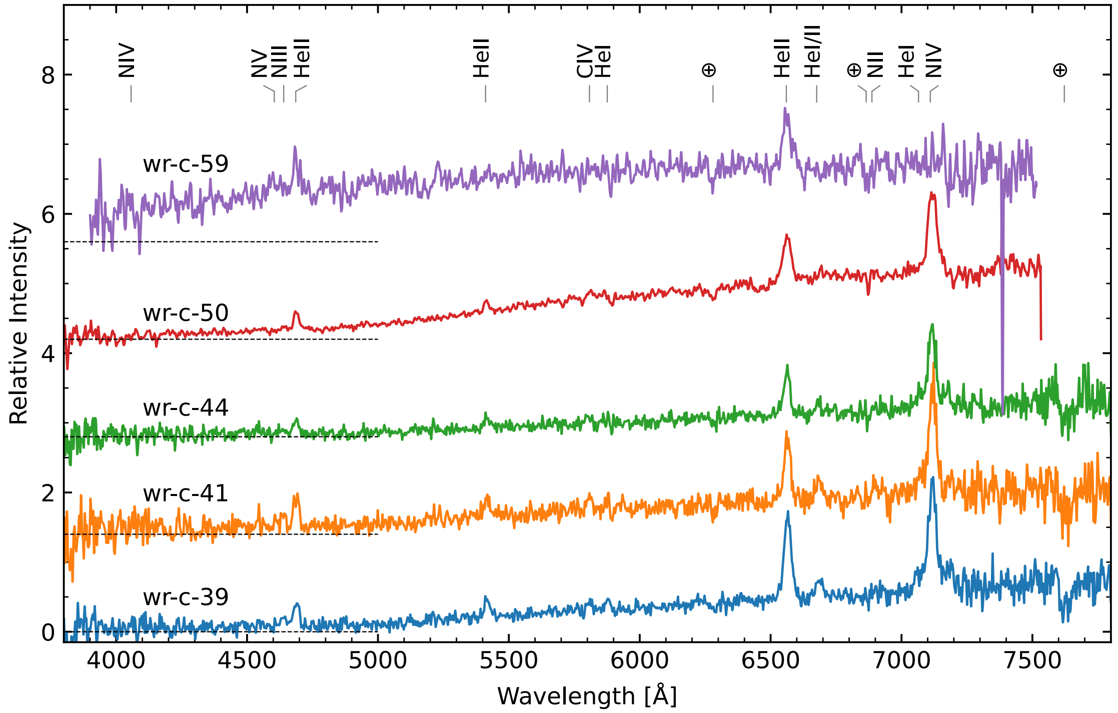


Fig. A.4. Possible WN stars for which we have only low S/N spectra available. WR-C-59 likely belongs to the WN3 subclass, WR-C-44, WR-C-41 and WR-C-50 to the range of subclasses WN5-6, and WR-C-39 to the range of subclasses WN7-8. The black dashed lines indicate the zero intensity scale of each spectrum. The position of the telluric absorption bands is marked with the symbol ⊕.

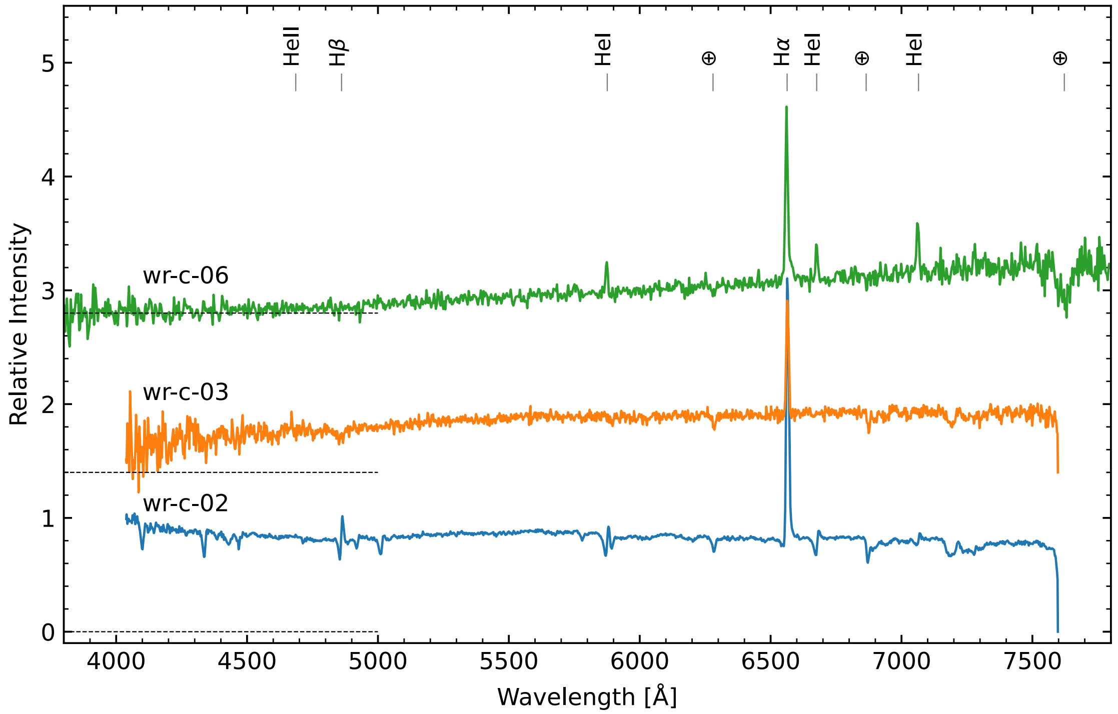


Fig. A.5. Observed candidates with non-WR spectra.The black dashed lines indicate the zero intensity scale of each spectrum. The position of the telluric absorption bands is marked with the symbol ⊕.