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Spectral atlas of the Galactic Wolf-Rayet stars (WN sequence) ⋆

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Abstract. Spectra of 62 (i.e. almost all) Galactic single Wolf-Rayet stars of the WN sequence are compiled. These data provided the empirical basis for our comprehensive spectral analyses of these stars published recently. The observations cover wide parts of the visual range and have a spectral resolution $\lambda/\Delta\lambda$ between 2000 and 3600 in most cases. Infrared observations around 10830 Å are included for 18 stars.

The spectra are preliminary "rectified" by division through an estimated stellar continuum. The whole material is displayed in concise plots sorted by spectral subtype in order to provide an overview. Access to the full digital data is offered via anonymous file transfer.

Key words: Stars: spectroscopy – Stars: Wolf-Rayet – Spectral atlas

1. Introduction

Since their discovery (Wolf & Rayet 1867) the Wolf-Rayet (WR) stars became a well-defined spectroscopic class, easily to be recognized by their broad and bright emission lines. The basic distinction between the WN (nitrogen) and WC (carbon) sequence was refined by definitions of spectral subtypes (Beals 1938, Hiltner & Schild 1966, Smith 1968).

An uniform atlas of WC spectra (absolutely calibrated, but with only moderate spectral resolution) has been published by Torres & Massey (1987). For WN stars, however, spectra are found only scattered over the literature (e.g., Smith & Kuhi 1981, Garmany et al. 1984, Lundström & Stenholm 1984, 1989). Therefore we want to present a comprehensive set of spectra comprising almost all Galactic single WN stars. These spectra were obtained with modern electronic detectors, and hence we can offer these data in digital form. Their resolution ($\lambda/\Delta\lambda$ between 2000 and 3600 in most cases) is sufficient with respect to the broad stellar features. The presented material provided the observational basis for our quantitative spectral analyses performed with the most advanced model atmosphere calculations (Schmutz et al. 1989, Hamann et al. 1993, 1994, 1995).

2. The spectra

2.1. The program stars and their spectral classification

The Sixth Galactic WR Catalogue (van der Hucht et al. 1981, updated by van der Hucht et al. 1988) comprises 71 stars of WN subtypes, when leaving aside those 14 stars classified as binary with luminous companion (i.e. with composite spectrum). More recent completions of the inventory (cf. van der Hucht 1995) are not yet accounted for in our sample. In the first column of Table 1 the Galactic single WN stars are identified by their number in the mentioned catalogs. The spectral subtype classification (Column 2) is also quoted from van der Hucht et al. (1988). Only for one star, WR 91, we have changed the classification from WN7 to WN6-s, cf. Hamann et al. 1993. The WN subtype number as originally defined by Smith (1968) reflects essentially the line strength ratios between different ionization stages of nitrogen. Remember that the subtypes WN2 to WN6 are called "early" (WNE), while from WN7 they are termed "late" (WNL). An additional "a" (abbreviating "+abs") is attributed according to van der Hucht et al. (1988) to those spectra showing not only emission, but also "absorption lines which have not been shown to be due to a companion". (Absorption features of that kind can be reproduced in principle by single-star models.) For WNE stars we append "-w" or "-s" to the classification, indicating whether the emission lines are weak or strong, respectively. The criterion (after its slight revision by Hamann et al. 1995) is whether the equivalent width of the He II line at 5412 Å is smaller or larger than 37 Å.

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⋆ Based, in part, on observations collected at the European Southern Observatory (ESO), La Silla, Chile

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Table 1. The Galactic single WN stars: subtypes, sources of our observations (abbreviations explained in the text) and key to the figures

WR (1)	subtype (2)	visual (3)	IR (4)	Fig. (5)
1	WN5-s	CA'93	-	1
2	WN2-w	CA'91	-	3
3	WN3a-w	CA'91	-	3
6	WN5-s	ESO'92	ESO'87	1
7	WN4-s	AAT'92	-	1
10	WN4.5-w	ESO'92	-	5
12	WN7	ESO'92	-	7
16	WN8	ESO'86	-	8
18	WN5-s	ESO'92	-	1
20	WN4.5-w	ESO'92	-	4
22	WN7a	ESO'92	ESO'87	8
24	WN7a	ESO'92	ESO'87	8
25	WN7a	ESO'92	ESO'87	8
28	WN7	-	-	-
29	WN7	-	-	-
34	WN4.5-w	ESO'92	-	4
35	WN6-w	ESO'92	-	5
36	WN4-s	ESO'92	-	1
37	WN3-s	ESO'92	ESO'92	1
40	WN8	ESO'86	ESO'87	8
44	WN4-w	ESO'92	-	3
46	WN3pec-w	ESO'93	ESO'87	3
49	WN5-w	ESO'92	ESO'92	5
51	WN4-w	ESO'92	ESO'92	3
54	WN4-w	ESO'92	ESO'92	3
55	WN7	ESO'92	-	6
58	WN4-s	ESO'92	-	1
61	WN4.5-w	ESO'92	ESO'92	4
62	WN6-s	ESO'92	ESO'92	2
63	WN6	-	-	-
66	WN8	ESO'92	-	8
67	WN6-w	ESO'92	ESO'92	4
71	WN6	-	-	-
74	WN7	ESO'92	-	6
75	WN6-s	ESO'92	ESO'87	2
78	WN7	ESO'92	ESO'87	7
82	WN8	ESO'92	-	9
83	WN6	-	-	-
84	WN6-w	ESO'92	-	4
85	WN6	-	-	-
87	WN7	ESO'92	-	7
89	WN7	ESO'92	-	7
91	WN6-s	ESO'92	-	2
94	WN6	-	-	-
100	WN6-s	ESO'92	-	2
105	WN8	CA'93	ESO'87	9
107	WN7-8	-	-	-
108	WN9	CA'93	ESO'87	9
109	WN3	-	-	-
110	WN6-s	CA'93	ESO'87	2

(to be continued)

Table 1. (continued)

WR (1)	subtype (2)	visual (3)	IR (4)	Fig. (5)
115	WN6-w	CA'91	-	4
116	WN8	CA'93	-	9
120	WN7	CA'91	-	6
123	WN8	CA'91	-	6
124	[WN8]?	CA'91	-	9
128	WN4-w	CA'91	-	5
129	WN4-w	CA'91	-	3
130	WN8	CA'93	-	9
131	WN7a	CA'91	-	8
134	WN6-s	CA'93	-	2
136	WN6-s	CA'91	-	2
138	WN6a-w	CA'91	-	5
141	WN6-w	CA'91	-	4
147	WN7	CA'93	-	7
148	WN7	CA'91	-	7
149	WN6-s	CA'93	-	2
152	WN3-w	CA'91	-	5
155	WN7	CA'93	-	6
156	WN8	CA'91	-	9
157*	WN4.5-w	CA'93	-	5
158	WN7	CA'91		7

* WR 157 is not resolved in our observation from its visual companion 1" apart, which is 0.2 mag brighter and of type B0III (Wilson 1940).

2.2. *The observations*

Spectra of 62 Galactic single WN stars have been taken by us on the occasion of different observation missions. The origin of the presented data is encoded in Table 1, Columns (3) and (4).

ESO'92 (visual): For objects of the southern hemisphere most visual spectra have been collected by U.W. between February 12 – 14, 1992, at the European Southern Observatory (ESO), La Silla, Chile, with the 3.6m telescope. Echelle spectra were taken with the ESO Faint Object Spectrograph and Camera (EFOSC) using the "blue" cross disperser and a TEK-CCD detector. The images contain nine useful echelle orders covering a total range from 3770 to 9055 Å with a spectral resolution $\lambda/\Delta\lambda$ of about 2000. Spectrograph and detector become less efficient below 4000 Å making the blue end of the spectra more noisy.
The EFOSC spectra were extracted from the two-dimensional image with software written in Kiel by G. Jonas. After division by a fit to the continuum of a comparison star, it was possible in most cases to rectify all orders together with a low-order polynomial function over the whole range. Sometimes single orders had to be rectified individually in order to obtain agreement in the overlapping parts.

ESO'93 (visual): One object (WR 46) was kindly observed for us by K. Werner on January 28, 1993, with the same equipment described in the previous item.

ESO'92 (infrared): Near-IR observations around 10830 Å were performed by U.W. between February 14 – 16, 1992, using the infrared spectrograph IRSPEC attached to the 3.5m New Technology Telescope (NTT). The detector was a two-dimensional InSb array (SBRC). The range 10830±250 Å was covered by three settings of the grating angle. The spectral resolution should be about 2500 theoretically, but seems actually to be lower (≈1000) in our data.
Stellar spectrum and background were extracted from two different strips on the detector array, interchanging these positions periodically in a series of 5 min exposures. The extracted pieces of a spectrum were divided by a continuum from a reference star, pasted together and rectified by a straight line.

ESO'87 (infrared): Near-IR observations around 10830 Å were also obtained with IRSPEC during an earlier mission by W.-R.H. (March 5 – 7, 1987). At that time the spectrograph was attached to the ESO 3.6m telescope and equipped with a one-dimensional array of 32 InSb diodes. Background subtraction was performed on-line by a "sky chopping" mode and beam switching. As described in the previous item, three settings of the grating angle covered the observed spectral range.

ESO'86 (visual): For two stars (WR 16 and WR 40) we had to refer to older spectra recorded with an Image Dissector Scanner (IDS). This detector was attached to the Boller & Chivens spectrograph at the 1.52m ESO telescope. These spectra cover the range from 3900 to 7300 Å with a resolution of about 10 Å. These observations were performed by W. Schmutz on May 7 – 8, 1986, and kindly provided for us.

AAT'92 (visual): For WR 7 we include a spectrum kindly provided by P. Crowther and L. Smith, taken in November 1992 at the 3.9m Anglo-Australian Telescope (AAT) at Siding Spring, Australia. With three settings of the grating the range from 3700 to 6000 Å was recorded with 1.7 Å resolution. Data reduction and spectrum rectification was performed by the observers in the usual way.

CA'91 (visual): Visual spectra of northern WN stars have been collected by W.-R.H. and L.K. between June 24 and July 1, 1991, at the "Deutsch-Spanisches Astronomisches Zentrum (DSAZ)", Calar Alto, Spain. We used the 2.2m-telescope with the Boller & Chivens Cassegrain spectrograph and a coated CCD (GEC). Three exposures per star were made with different grating angles, covering the spectral range from 3320 Å to 7400 Å with a spectral resolution of about 3600.
The spectra were extracted from the images with the software written in Kiel. After division by a fit to the continuum of a comparison star, the continuum was defined in each of the three parts of the spectrum by fitting a low-order polynomial.

CA'93 (visual): The identical equipment was used again 1993 (July 3 – 12) by W.-R.H. and U.W., but the data reduction was now performed with the MIDAS software from ESO.

All spectra were wavelength-calibrated without any radial velocity correction.

2.3. Graphic representation

A concise graphic representation of the spectra is given in Figs. 1–9. The spectra are arranged in different subtype sequences, distinguishing between the following spectral subclasses.

Figs. 1–2: early-type WN stars with strong lines (WNE-s)
Figs. 3–4: early-type WN stars with weak lines (WNE-w) not showing hydrogen
Fig. 5: early-type WN stars with weak lines (WNE-w) showing hydrogen
Fig. 6: late-type WN stars (WNL) not showing hydrogen
Figs. 7–9: late-type WN stars (WNL) showing hydrogen

Concerning the presence or absence of hydrogen, the information is taken from Hamann et al. (1993 and 1995). Individual stars can be found quickly by the help of the last column in Table 1.

If the emission at 4686 Å is too strong to fit into the diagram, it is displayed as little inset scaled down by the factor four. Double lines appearing in the tracings reflect overlapping spectral sections or echelle orders. If inconsistent, the middle part of a spectral section or echelle order should be more reliable than the ends. Very noisy parts (e.g. the bluemost echelle order of some EFOSC spectra) have been smoothed for the graphic representation, but the original data are contained in the data bank (see below). The most prominent spectral features are identified in the figures at their laboratory wavelengths. More detailed identifications can be found, e.g., in Hamann et al. (1994) or Smith & Kuhi (1981).

2.4. The data bank

The presented spectra can be retrieved from our anonymous ftp server saturn.astrophysik.uni-kiel.de alias 134.245.66.1 (username: *anonymous*, password: give your e-mail address). The data are stored in ASCII files in the directory pub/WRHamann/WNatlas. Filenames encode the WR number and the wavelength range. Organization of the data tables is self-explaining: one data pair per line gives the wavelength in Å and the normalized flux. Part of the IR spectra (ESO'87) are over μm. Obviously bad data are sometimes commented by an asterisk as first character of the line. Some additional lines at the beginning and the end of each table are to be considered as comment, too. Each spectrographic exposure forms its own file. Thus an EFOSC echelle spectrum (ESO'92) is given in one file, containing nine tables for each spectral order which are separated by comment lines.

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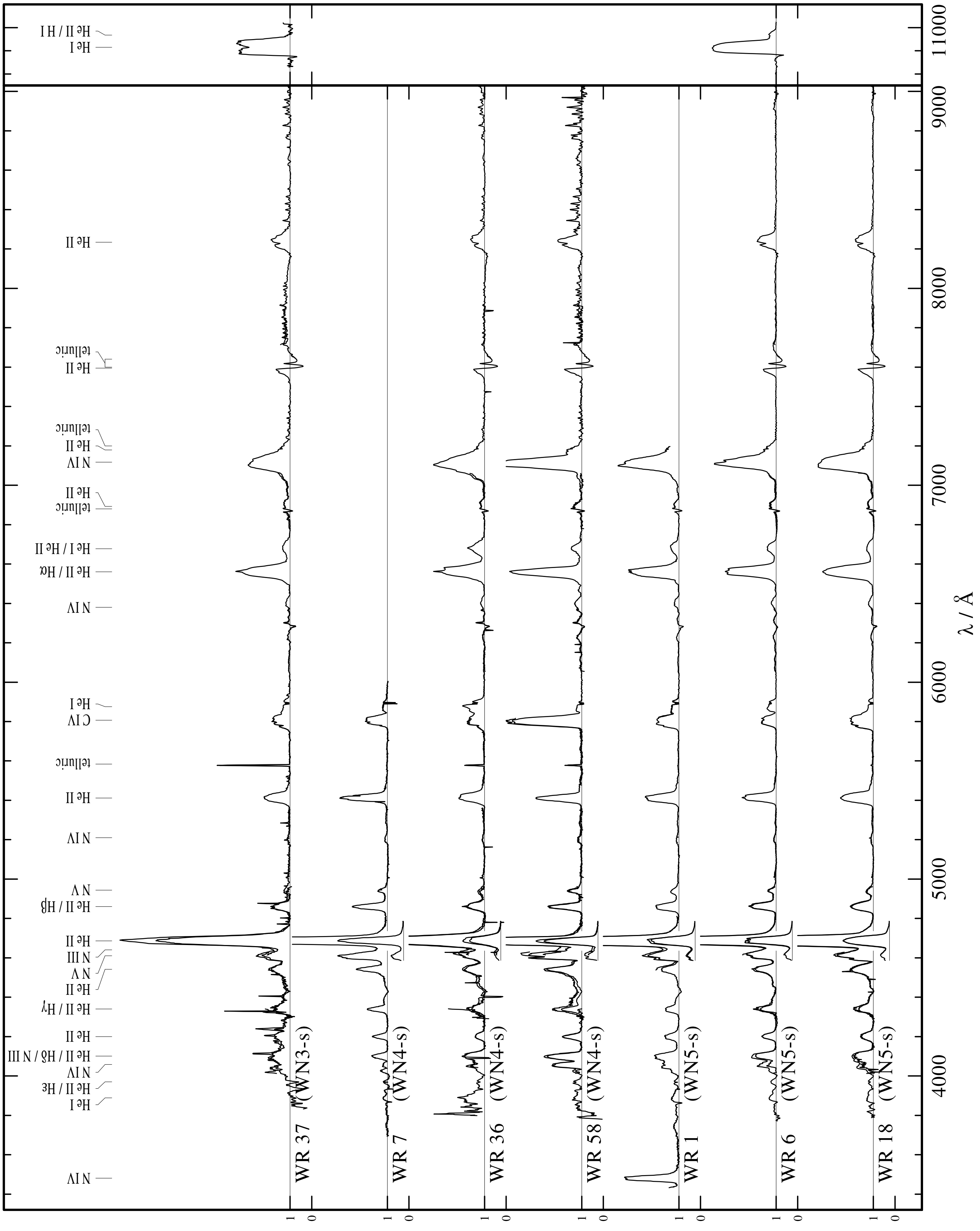

Fig. 1. Normalized spectra of early subtypes with strong lines (WNE-s) – part 1: WN3-s to WN5-s

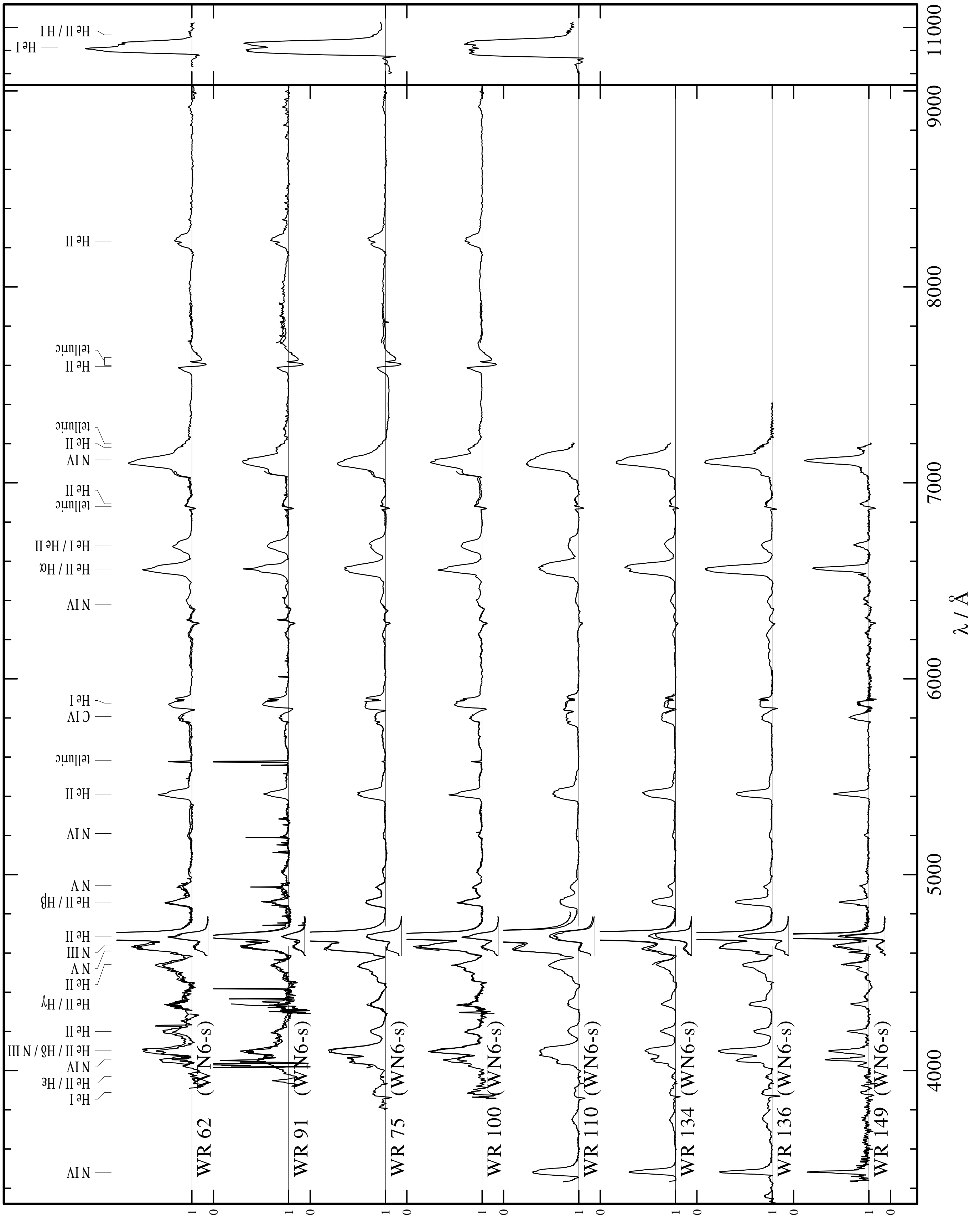

Fig. 2. Normalized spectra of early subtypes with strong lines (WNE-s) – part 2: WN6-s

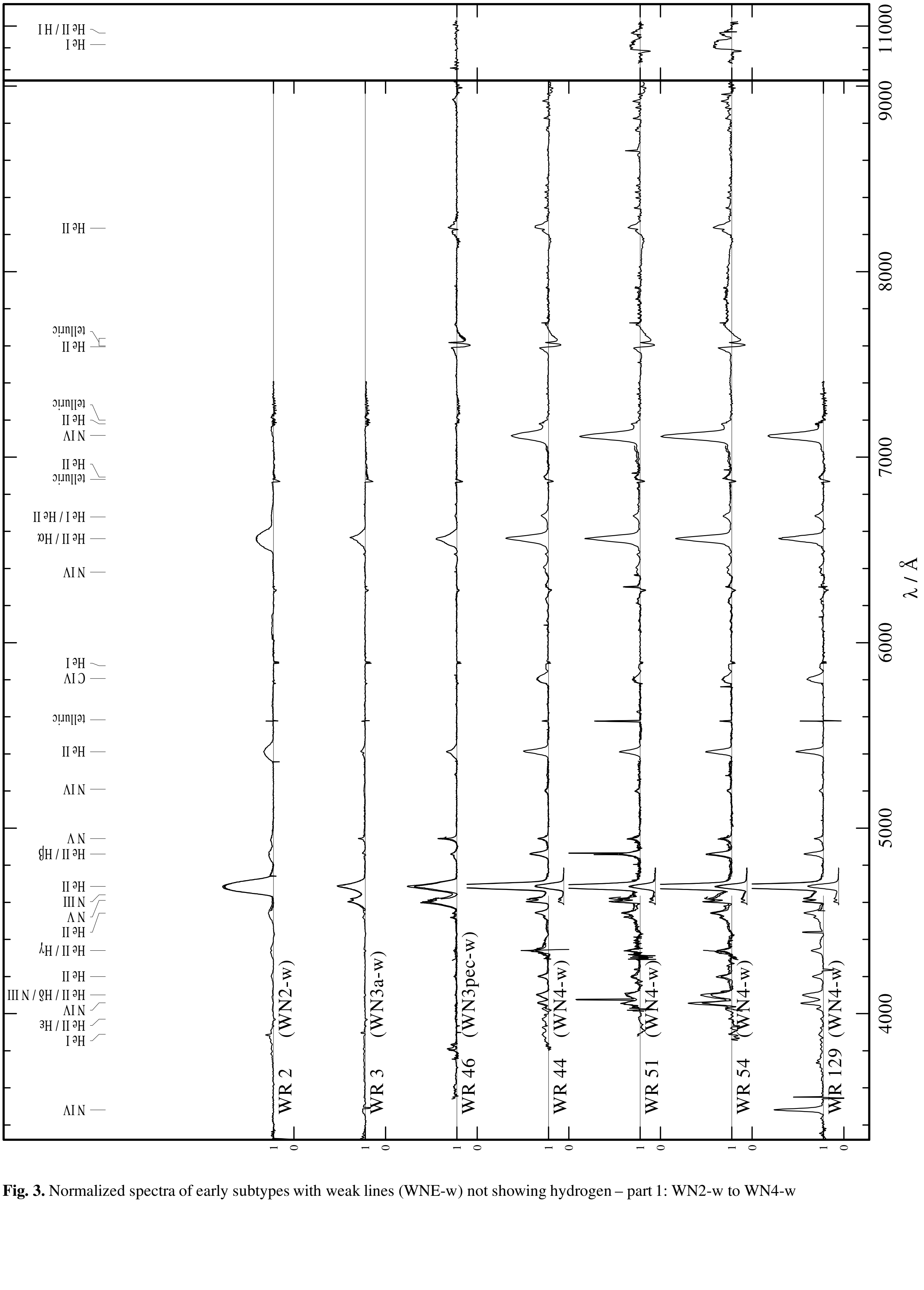

Fig. 3. Normalized spectra of early subtypes with weak lines (WNE-w) not showing hydrogen – part 1: WN2-w to WN4-w

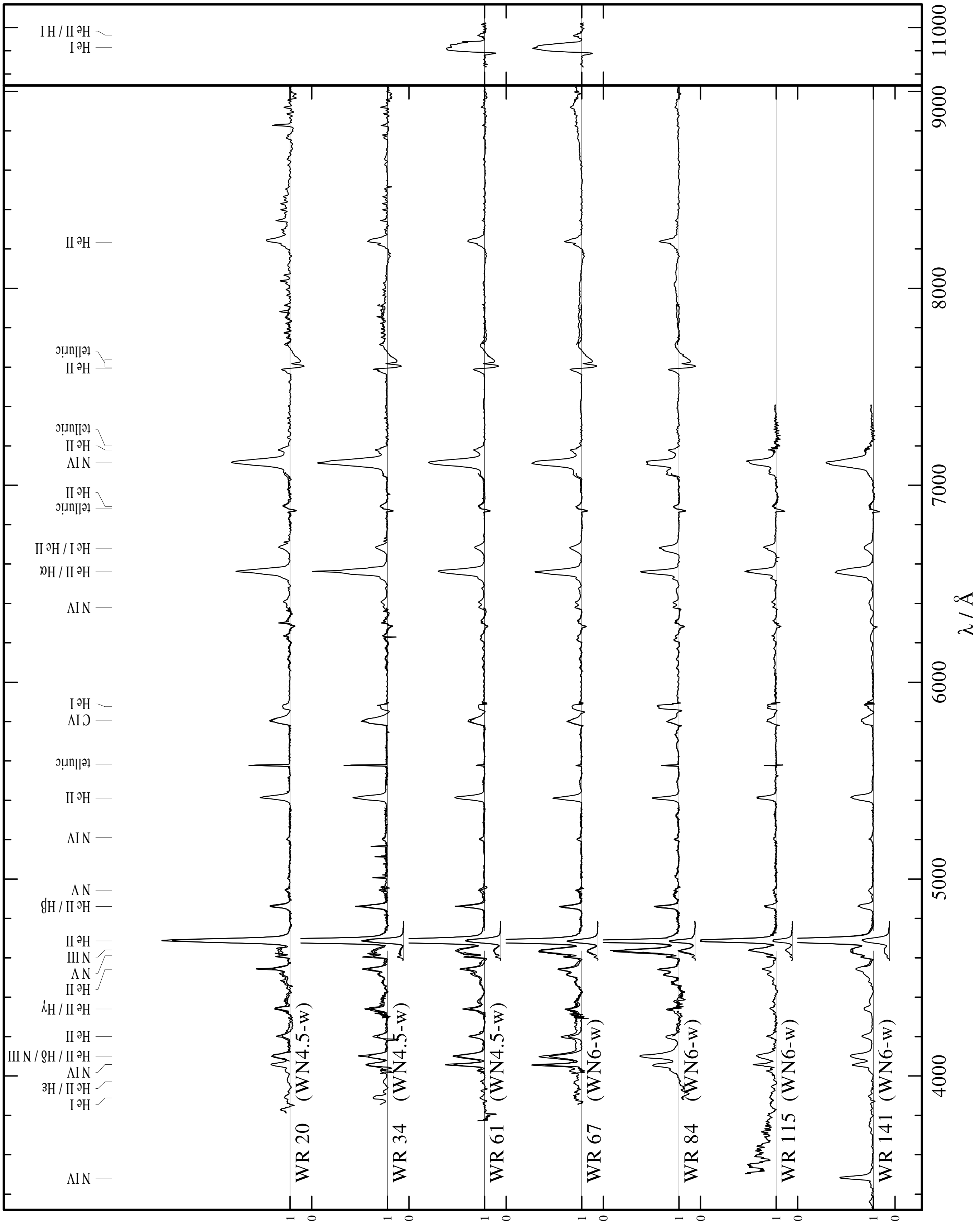

Fig. 4. Normalized spectra of early subtypes with weak lines (WNE-w) not showing hydrogen – part 2: WN4.5-w to WN6-w

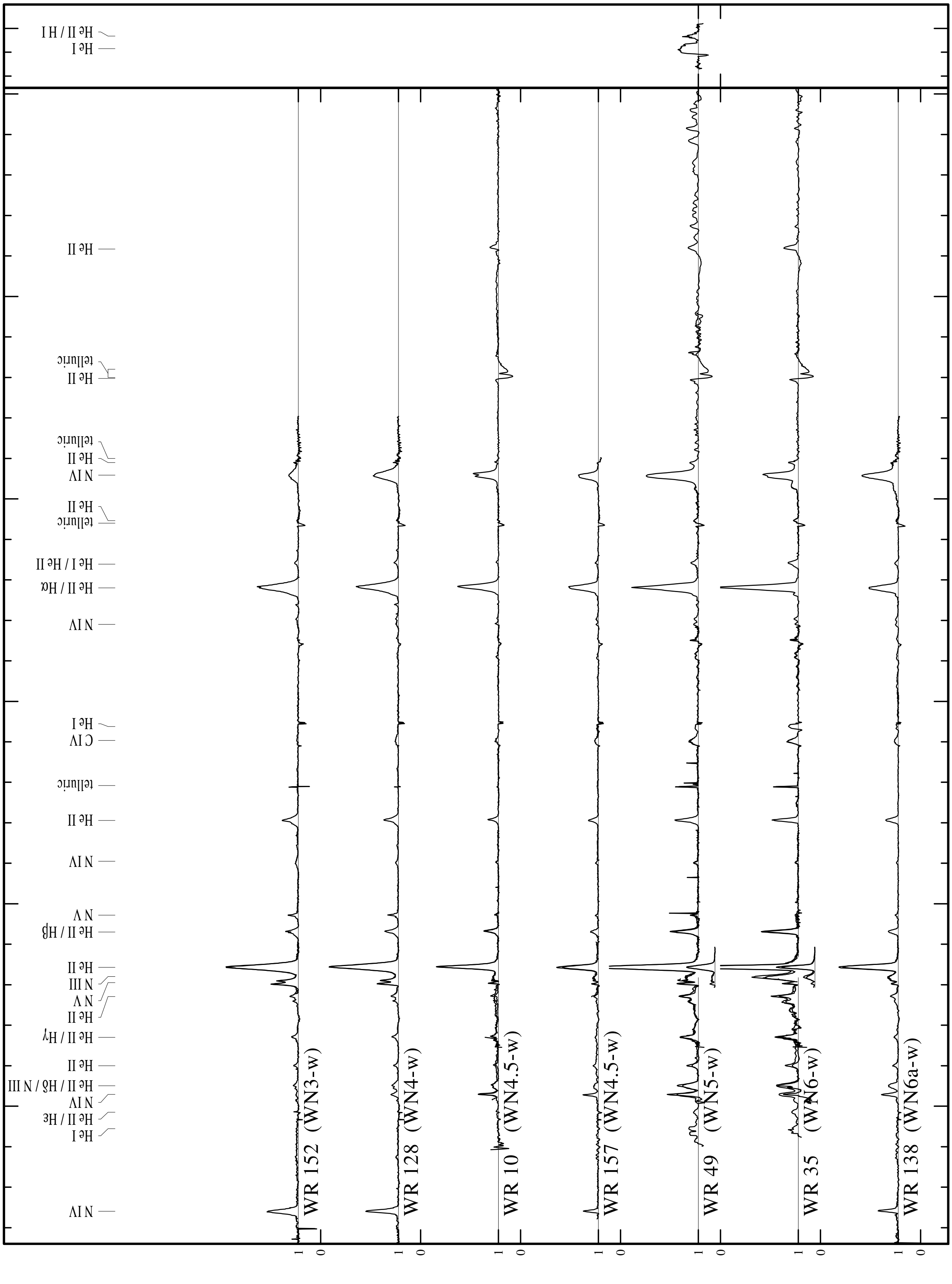

Fig. 5. Normalized spectra of early subtypes with weak lines (WNE-w) showing hydrogen

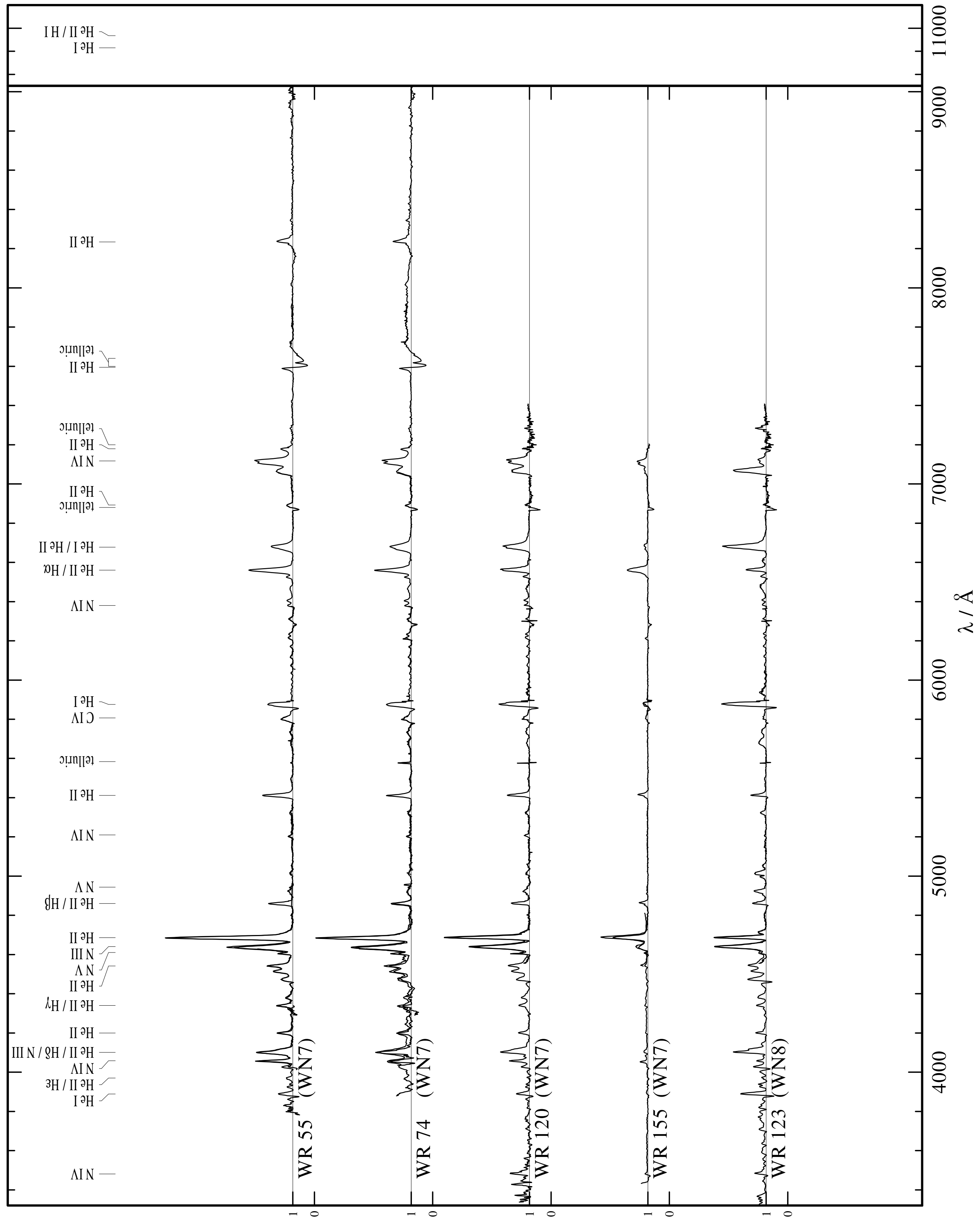

Fig. 6. Normalized spectra of late subtypes (WNL) not showing hydrogen

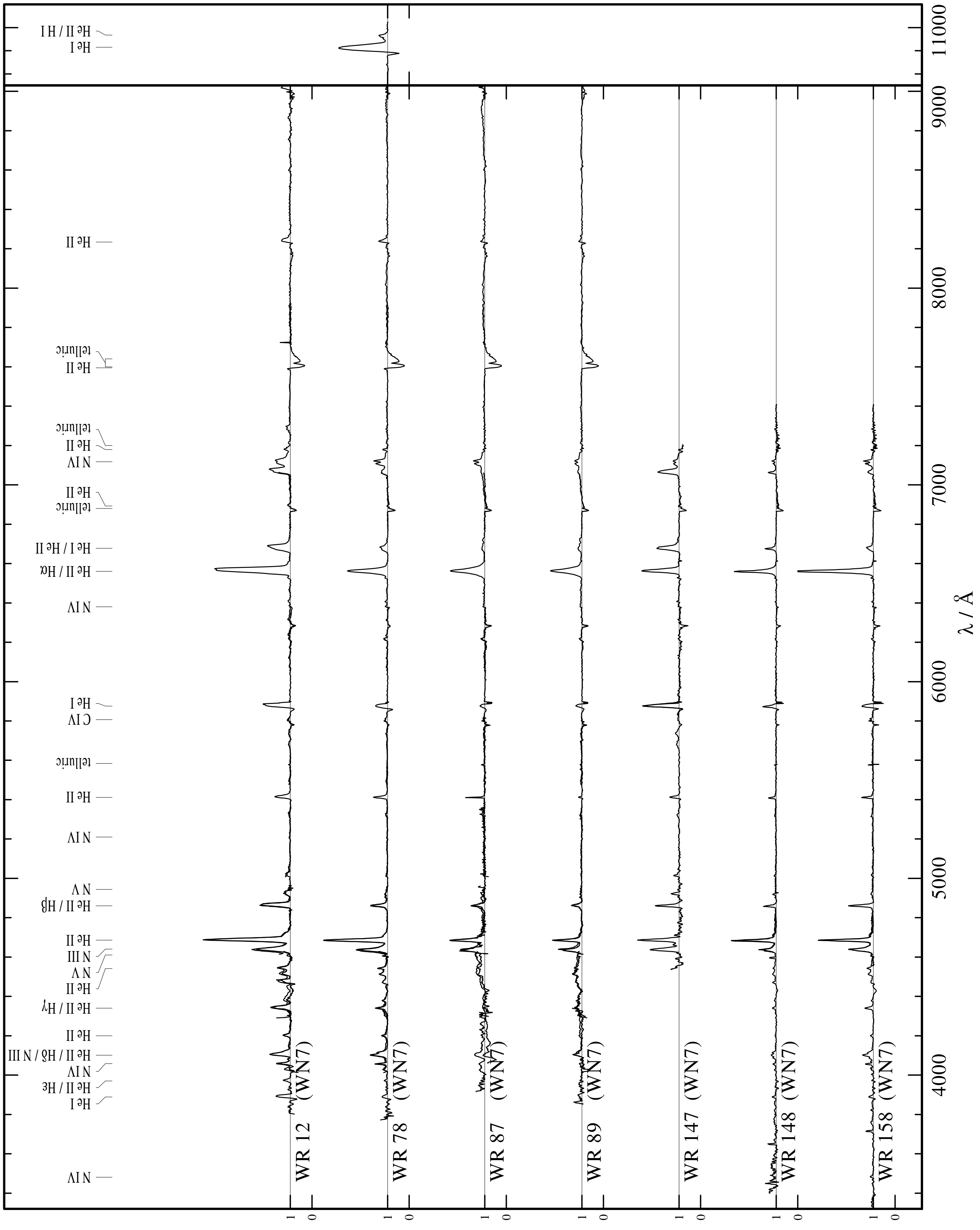

Fig. 7. Normalized spectra of the late subtypes (WNL) showing hydrogen – part 1: WN7 (to be continued)

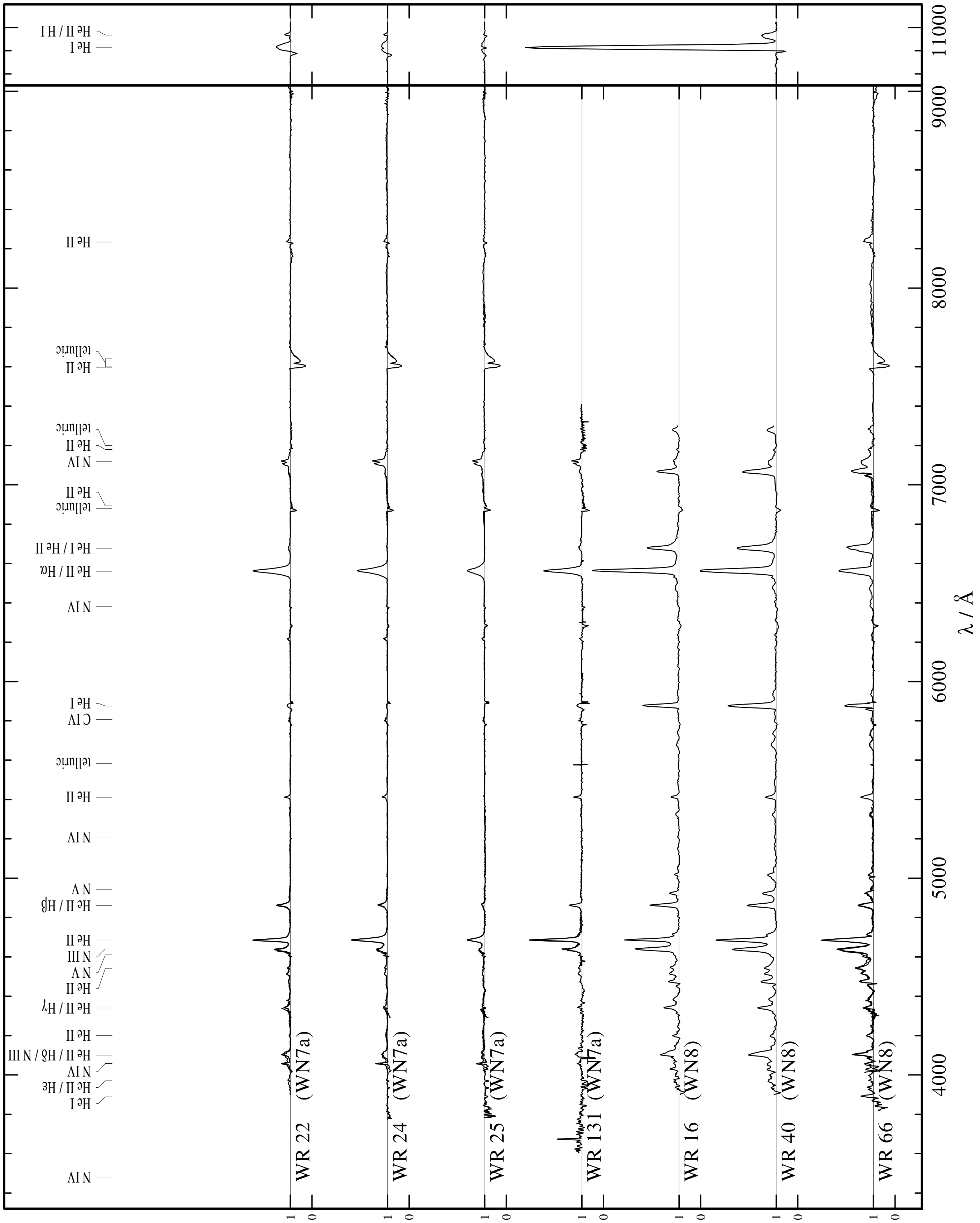

Fig. 8. Normalized spectra of the late subtypes (WNL) showing hydrogen – part 2: WN7 (continued) to WN8 (to be continued)

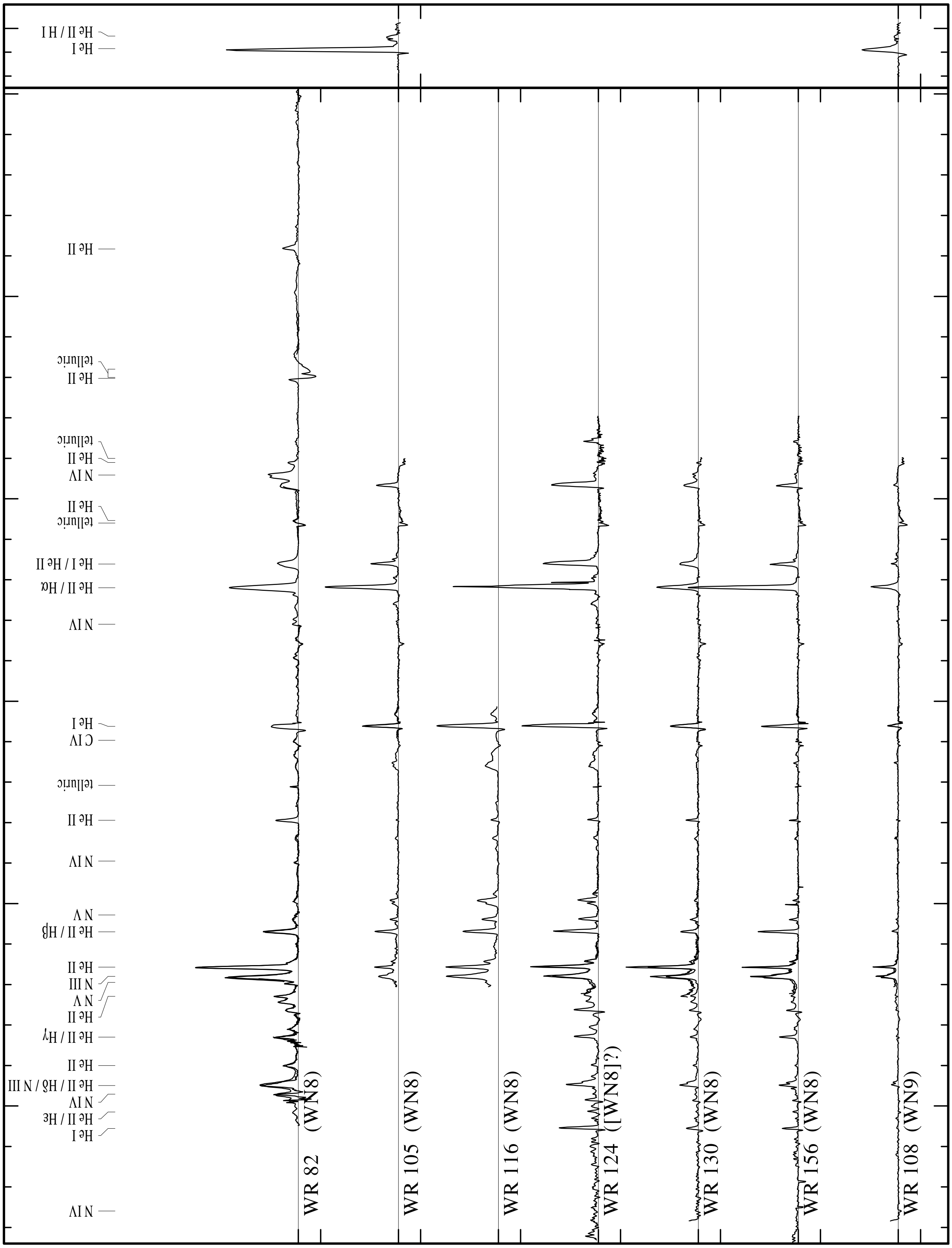

Fig. 9. Normalized spectra of the late subtypes (WNL) showing hydrogen – part 3: WN8 (continued) and WN9