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# A NEAR-INFRARED SURVEY OF THE INNER GALACTIC PLANE FOR WOLF-RAYET STARS. II. GOING FAINTER: 71 MORE NEW W-R STARS

Michael M. Shara[1,5], Jacqueline K. Faherty[1,5], David Zurek[1,5], Anthony F. J. Moffat[2], Jill Gerke[3], René Doyon[2], Etienne Artigau[4], and Laurent Drissen[4]
[1] American Museum of Natural History, 79th Street and Central Park West, New York, NY 10024-5192, USA; mshara@amnh.org, jfaherty@amnh.org, dzurek@amnh.org
[2] Département de Physique, Université de Montréal, CP 6128, Succ. C-V, Montréal, QC, H3C 3J7, Canada; moffat@astro.umontreal.ca, doyon@astro.umontreal.ca
[3] Department of Astronomy, Ohio State University, Columbus, OH 43210-1173, USA; gerke@astronomy.ohio-state.edu
[4] Département de Physique, Université Laval, Pavillon Vachon, Quebec City, QC, G1K 7P4 Canada; artigau@astro.umontreal.ca, ldrissen@phy.ulaval.ca
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## ABSTRACT

We are continuing a $J$, $K$ and narrowband imaging survey of 300 deg$^2$ of the plane of the Galaxy, searching for new Wolf–Rayet (W-R) stars. Our survey spans 150° in Galactic longitude and reaches 1° above and below the Galactic plane. The survey has a useful limiting magnitude of $K = 15$ over most of the observed Galactic plane, and $K = 14$ (due to severe crowding) within a few degrees of the Galactic center. Thousands of emission-line candidates have been detected. In spectrographic follow-ups of 146 relatively bright W-R star candidates, we have re-examined 11 previously known WC and WN stars and discovered 71 new W-R stars, 17 of type WN and 54 of type WC. Our latest image analysis pipeline now picks out W-R stars with a 57% success rate. Star subtype assignments have been confirmed with the $K$-band spectra and distances approximated using the method of spectroscopic parallax. Some of the new W-R stars are among the most distant known in our Galaxy. The distribution of these new W-R stars is beginning to trace the locations of massive stars along the distant spiral arms of the Milky Way.

*Key words:* Galaxy: disk – Galaxy: stellar content – infrared: stars – stars: emission-line, Be – stars: Wolf-Rayet – surveys

## 1. INTRODUCTION AND MOTIVATION

Most Population I Wolf–Rayet (W-R) stars are the helium-burning descendants of the most massive stars (with initial masses greater than $\sim 20\, M_\odot$ at $Z_\odot$). They are also among the most luminous stars known. Their powerful winds ($\dot{M} \sim 10^{-5}\, M_\odot\, \mathrm{yr}^{-1}$) display strong, broad emission lines of helium, and either nitrogen (WN subtypes) or carbon/oxygen (WC/WO subtypes)—the defining observational characteristics of W-R stars. Because of their relatively short lifetimes (about $5 \times 10^5$ years, which is roughly 10% of the star's total lifetime), W-R stars are excellent tracers of recent star formation. They are also believed to be Type Ib or Ic supernova progenitors, because they have removed their outer H-rich layers (WN) or even He-rich layers (WC/WO) (but see also Smartt 2009).

Galactic distribution models predict that ∼1000–6500 W-R stars are expected (Shara et al. 1999, 2009; van der Hucht 2001) in total, but this assumes that massive stars are uniformly distributed throughout the Milky Way. If the total W-R star population is as high as 6500, then one might erupt as a Type Ib or Ic supernova within a few generations, as each lasts $\sim 5 \times 10^5$ years. The clear identification of a W-R star as the progenitor of one of these eruptions would be a dramatic confirmation of a key prediction of stellar evolution theory. It would be no less valuable to show that a Type Ib or Ic progenitor did not have a W-R star progenitor.

The prediction of a second test of massive star evolution theory follows from the radial metallicity gradient across our Galaxy (Smartt & Rolleston 1997). Higher $Z$ is predicted to lead to stronger stellar winds that reveal the deeper parts of massive stars more quickly. This suggests that the WC/WN number ratio must increase sharply in the inner parts of the Milky Way relative to what we observe in the solar neighborhood (Meynet & Maeder 2005). This is consistent with what is presently observed (Shara et al. 1999), but before we began the survey that is the subject of this paper only about 300 W-R stars had been identified in the Milky Way (van der Hucht 2006). Carrying out these important tests of stellar evolution theory demands a much larger and more complete census of Galactic W-R stars—particularly in regions at different $Z$ than the solar neighborhood—than has hitherto been possible. Optical narrowband surveys have been severely limited by interstellar extinction (Shara et al. 1999), so a majority of the known W-R stars lie within a few kiloparsecs of the Sun. The only reasonable way to locate the vast majority of the Galactic W-R stars is to search for them in the near-infrared where the Milky Way is quite transparent.

In Shara et al. (2009, hereafter Paper I), we described a new narrowband infrared imaging survey of much of the Galactic plane. The goal outlined in that paper was to locate and characterize 90% of the W-R stars in the Galaxy within a decade. Details of the infrared camera, filters, telescope, and image processing used to reduce the 77,000 science and dome flat images (taken in 2005 and 2006) are given in Paper I. We also described our candidate selection criteria and focused on 173 bright candidate targets with emission-band magnitudes brighter than $K = 11.5$ for follow-up spectroscopy. Our exploratory 2007 spectrographic run, detailed in Paper I, resulted in the confirmation of 41 new W-R stars: 15 WN and 26 WC, and represented a nearly 24% success rate.

This paper reports the results of further follow-up spectroscopy (carried out in 2009) of 146 candidates brighter than $K = 12.5$. We continued to use the aperture photometry methodology described in Paper I to compare the magnitudes of all the stars detected in both broadband and narrowband (He I, He II,

[5] Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement no. NNX-08AE38A with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.

**Table 1**
Previously Identified W-R Stars

| Name (1) | α(J2000) (2) | δ(J2000) (3) | $l$ (4) | $b$ (5) | $B$[a] (6) | $V$[a] (7) | $R$[a] (8) | $J$[a] (9) | $H$[a] (10) | $K_s$[a] (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1059-62L | 16 14 37.25 | −51 26 26.4 | 331.81 | −0.34 | ... | ... | ... | 15.048 | 12.788 | 11.54 |
| 1081-76L | 16 24 58.87 | −48 56 52.6 | 334.75 | 0.27 | ... | ... | ... | 13.282 | 11.763 | 10.73 |
| 1093-87L | 16 31 29.21 | −47 56 16.3 | 336.22 | 0.19 | ... | ... | ... | 15.555 | 12.855 | 11.32 |
| 1093-80L | 16 31 49.06 | −47 56 04.6 | 336.26 | 0.15 | ... | ... | ... | 15.108 | 12.862 | 11.47 |
| 1095-98L | 16 35 23.21 | −48 09 16.2 | 336.51 | −0.43 | ... | ... | ... | 14.900 | 12.770 | 11.43 |
| 1218-38L | 17 22 40.75 | −35 04 52.8 | 352.20 | 0.74 | ... | ... | ... | 15.105 | 12.044 | 10.33 |
| 1385-9L | 18 13 42.49 | −17 28 12.3 | 13.15 | 0.13 | ... | ... | 20.02 | 11.205 | 9.699 | 8.57 |
| 1425-15L | 18 23 03.41 | −13 10 00.5 | 18.01 | 0.18 | 15.23 | 14.49 | 14.41 | 10.339 | 9.282 | 8.27 |
| 1428-157L | 18 25 53.09 | −13 28 32.5 | 18.05 | −0.57 | 16.07 | 15.13 | ... | 10.317 | 9.521 | 8.96 |
| 1505-86L | 18 41 48.47 | −04 00 12.8 | 28.27 | 0.31 | ... | ... | ... | 15.618 | 13.323 | 11.99 |
| 1613-50L | 19 06 36.53 | +07 29 52.4 | 41.33 | 0.06 | ... | ... | ... | 14.237 | 12.65 | 11.61 |
| 1671-32L | 19 20 40.40 | +13 50 35.1 | 48.55 | −0.05 | ... | ... | ... | 13.573 | 11.804 | 10.76 |

**Notes.** Previously identified Wolf-Rayet stars from Shara et al. (2009) that were observed using SpeX. A lack of *BVR* data implies that the star is below the 21st magnitude plate limits of the digitized sky surveys.
[a] The *B*, *V*, and *R* photometry comes from the NOMAD catalog, while *J*, *H*, and $K_s$ photometry comes from the Two Micron All Sky Survey (2MASS).

C IV, and Brackett-gamma) images. We compared candidates' images carefully by eye to remove spurious or doubtful stars and culled stars of lower statistical significance. This resulted in a significantly higher success rate than reported in Paper I. After this paper was completed, a complementary effort to locate W-R stars using NIR and mid-IR colors was published by Mauerhan et al. (2011). Using the technique first outlined by Hadfield et al. (2007), they located 60 new W-R stars. In Section 2, we describe our spectrographic observations and the data reduction procedure we used. We present the spectra and spectral types, and derive the distances and spatial distribution in the Galaxy of our new W-R stars in Section 3. In Section 4, we briefly note a new ring nebula W-R star and two W-R stars in a compact cluster. In Section 5, we discuss the completeness of this survey, and the complementarity of the narrowband and color-based surveys. The finder charts of the new W-R stars are presented in Section 6, and we summarize our results in Section 7.

## 2. OBSERVATIONS: NEAR-INFRARED SPECTROSCOPY WITH SpeX

Near-IR spectra were obtained of 146 candidate W-R stars with the SpeX spectrograph mounted on the 3 m NASA Infrared Telescope Facility (IRTF) over 11 half-nights in 2009 August. The conditions of this run were excellent with average seeing (0$''$.5–0$''$.8 at *J*). We operated in cross-dispersed mode with the 0$''$.5 slit aligned and obtained an average resolving power of $\lambda/\Delta\lambda \sim 1200$. The near-infrared spectral data spanned 0.8–2.4 $\mu$m. Each target was first acquired in the guider camera. We evaluated each candidate after a single AB dither pattern with exposure times varying from 30 s for our brightest targets to 200 s for our faintest. Once we had confirmed the presence of emission lines, we began a second set of AB images so each W-R star had four images obtained with an ABBA dither pattern along the slit. To minimize slew and calibration target time, we chose subsequent targets closeby in the sky. An A0V star was observed after each several targets (typically 4–5) at a similar airmass for flux calibration and telluric correction. Internal flat-field and Ar arc lamp exposures were also acquired for pixel response and wavelength calibration, respectively. We also acquired a spectrum of almost all known spectral subtypes of W-R star. All data were reduced using SpeXtool version 3.3 (Cushing et al. 2004) using standard settings.

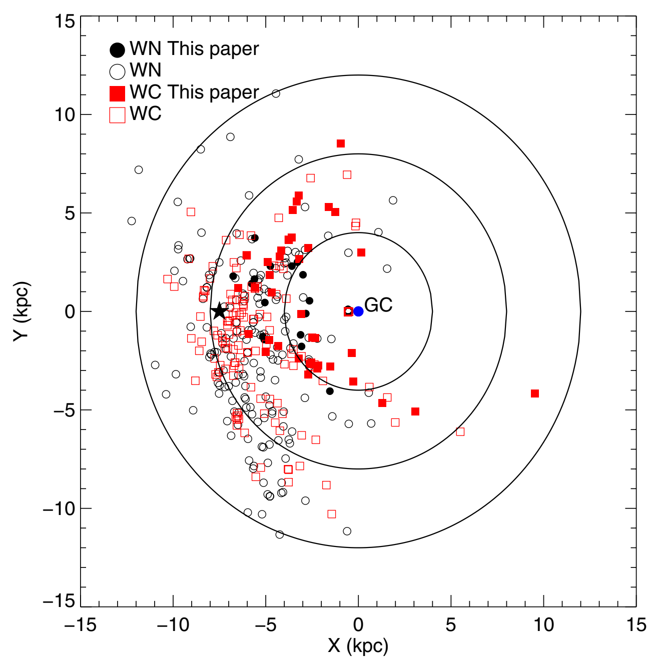


**Figure 1.** Galactic distribution of known and new W-R stars with estimated distances projected on the plane. New WC and WN stars are filled boxes and circles, respectively, while known WC and WN stars are unfilled. The Galactic center (GC) is labeled as is the position of the Sun (black five-point star). Circles of radius 4, 8, and 12 kpc are overplotted.

## 3. SPECTRAL CLASSIFICATION AND SPATIAL DISTRIBUTION

The classification was carried out using the guiding principles of near-infrared classification of W-R stars according to Crowther et al. (2006), supplemented by the spectra that were taken at IRTF for stars of known type [WR152 WN3(h), WR127 (WN5o + O), WR138 (WN5+B), WR134 (WN6), WR120 (WN7), WR123 (WN8), WR108 (WN9h + OB); WR142 (WO2), WR143 (WC4 + OB?), WR111 (WC5), WR126 (WC5/WN), WR154 (WC6), WR137 (WC7pd + O), WR135 (WC8), WR121 (WC9d)]. These spectra of W-R stars, which have been well studied in the optical—using the same setup as the candidate W-R stars—often helped decide borderline cases. The classification was made by eye, comparing

**Table 2**
New W-R Stars

| Name (1) | α(J2000) (2) | δ(J2000) (3) | l (4) | b (5) | $B$ [a] (6) | $V$ [a] (7) | $R$ [a] (8) | $J$ [a] (9) | $H$ [a] (10) | $K_s$ [a] (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1023-63L | 15 52 09.48 | −54 17 14.5 | 327.39 | −0.23 | ... | ... | ... | 16.13 | 15.06 | 14.37 |
| 1042-25L | 16 00 25.25 | −52 03 29.6 | 329.77 | 0.68 | ... | ... | ... | 12.02 | 10.65 | 9.88 |
| 1038-22L | 16 00 26.41 | −52 11 10.1 | 329.69 | 0.58 | ... | ... | 19.70 | 11.53 | 10.20 | 9.29 |
| 1054-43L | 16 10 06.26 | −50 47 58.6 | 331.74 | 0.61 | ... | ... | ... | 15.62 | 13.05 | 11.53 |
| 1051-67L | 16 10 06.67 | −51 47 24.5 | 331.07 | −0.11 | ... | ... | ... | 14.86 | 12.63 | 11.24 |
| 1077-55L | 16 24 22.70 | −49 00 42.3 | 334.63 | 0.30 | ... | ... | ... | 15.15 | 13.13 | 11.97 |
| 1085-72L | 16 27 42.39 | −48 30 34.2 | 335.37 | 0.25 | ... | ... | ... | 14.50 | 12.37 | 11.21 |
| 1085-69L | 16 28 40.25 | −48 18 12.9 | 335.63 | 0.28 | ... | ... | ... | 14.73 | 13.16 | 11.50 |
| 1085-83L | 16 29 35.82 | −48 19 34.2 | 335.72 | 0.15 | ... | ... | ... | 16.70 | 13.49 | 11.83 |
| 1093-138L | 16 32 15.22 | −47 56 12.7 | 336.31 | 0.10 | ... | ... | ... | 16.00 | 14.17 | 12.75 |
| 1093-140LB | 16 32 47.99 | −47 44 53.2 | 336.51 | 0.16 | ... | 17.74 | ... | 15.79 | 14.29 | 13.99 |
| 1093-140L | 16 32 49.78 | −47 44 31.4 | 336.52 | 0.16 | ... | ... | ... | 16.15 | 13.97 | 12.28 |
| 1091-46L | 16 33 14.06 | −48 17 37.2 | 336.16 | −0.26 | ... | ... | ... | 13.93 | 11.76 | 10.02 |
| 1093-59L | 16 33 45.45 | −47 51 29.1 | 336.54 | −0.03 | ... | ... | ... | 15.56 | 12.98 | 11.41 |
| 1095-189L | 16 33 48.13 | −47 52 52.8 | 336.53 | −0.05 | ... | ... | ... | 10.43 | 9.62 | 9.35 |
| 1097-156L | 16 34 57.45 | −47 04 13.0 | 337.26 | 0.35 | ... | ... | ... | 13.75 | 11.71 | 10.46 |
| 1097-71L | 16 35 44.37 | −47 19 42.2 | 337.16 | 0.08 | ... | ... | ... | 15.28 | 13.72 | 12.04 |
| 1097-34L | 16 35 51.16 | −47 19 51.3 | 337.17 | 0.06 | ... | ... | ... | 13.60 | 11.67 | 10.39 |
| 1106-31L | 16 37 24.00 | −46 26 28.6 | 338.00 | 0.47 | 17.78 | 15.29 | 13.31 | 10.27 | 9.59 | 8.93 |
| 1105-76L | 16 38 20.18 | −46 23 43.8 | 338.14 | 0.38 | ... | ... | ... | 14.77 | 12.74 | 11.48 |
| 1109-74L | 16 40 17.12 | −46 20 09.7 | 338.41 | 0.17 | ... | ... | ... | 16.92 | 13.10 | 11.25 |
| 1115-197L | 16 43 40.36 | −45 57 57.5 | 339.08 | −0.03 | 18.20 | 16.73 | 14.59 | 10.56 | 9.71 | 9.14 |
| 1138-133L | 16 51 19.32 | −43 26 55.3 | 341.88 | 0.56 | ... | ... | ... | 13.56 | 11.93 | 10.95 |
| 1133-59L | 16 51 29.69 | −43 53 35.3 | 341.55 | 0.25 | ... | ... | ... | 14.73 | 13.46 | 12.06 |
| 1168-91L | 17 09 32.64 | −41 29 47.3 | 345.48 | −0.88 | ... | ... | ... | 15.13 | 13.43 | 11.84 |
| 1179-129L | 17 11 00.84 | −39 49 31.2 | 346.99 | −0.12 | ... | ... | ... | 15.26 | 13.89 | 12.81 |
| 1181-82L | 17 11 28.52 | −39 13 16.8 | 347.53 | 0.17 | ... | ... | ... | 13.98 | 12.20 | 10.98 |
| 1181-81L | 17 11 36.12 | −39 11 07.9 | 347.58 | 0.17 | ... | ... | ... | 13.35 | 12.08 | 10.81 |
| 1181-211L | 17 11 46.14 | −39 20 27.7 | 347.47 | 0.05 | 20.75 | 17.70 | 16.33 | 10.88 | 10.00 | 9.49 |
| 1189-110L | 17 14 09.56 | −38 11 20.9 | 348.68 | 0.35 | ... | ... | ... | 14.34 | 12.78 | 11.59 |
| 1245-23L | 17 33 33.22 | −32 36 16.4 | 355.52 | 0.24 | ... | ... | ... | 15.99 | 12.59 | 10.76 |
| 1269-166L | 17 41 13.51 | −30 03 41.1 | 358.54 | 0.22 | ... | ... | ... | 13.52 | 11.70 | 10.56 |
| 1275-184L | 17 44 06.89 | −30 01 13.2 | 358.90 | −0.29 | ... | ... | ... | 13.90 | 11.52 | 10.17 |
| 1322-220L | 17 55 20.21 | −24 07 38.2 | 5.24 | 0.60 | 19.93 | ... | 16.80 | 11.84 | 10.95 | 10.32 |
| 1327-25L | 17 59 02.86 | −24 20 51.12 | 5.48 | −0.24 | ... | ... | ... | 13.78 | 12.38 | 10.89 |
| 1342-208L | 17 59 48.22 | −22 14 52.4 | 7.38 | 0.65 | ... | ... | 17.71 | 11.40 | 10.29 | 9.47 |
| 1381-20L | 18 12 57.27 | −18 01 20.7 | 12.58 | 0.02 | ... | ... | ... | 14.24 | 13.35 | 10.75 |
| 1395-86L | 18 16 02.36 | −16 53 59.4 | 13.92 | −0.09 | ... | ... | ... | 18.08 | 13.96 | 11.85 |
| 1434-43L | 18 23 32.32 | −12 03 58.5 | 19.03 | 0.59 | ... | ... | ... | 14.45 | 12.90 | 11.69 |
| 1431-34L | 18 25 53.63 | −12 50 03.0 | 18.62 | −0.27 | 20.65 | ... | 17.43 | 11.53 | 10.13 | 9.28 |
| 1463-7L | 18 33 47.64 | −09 23 07.7 | 22.58 | −0.39 | ... | ... | ... | 12.18 | 10.52 | 9.36 |
| 1477-55L | 18 35 47.67 | −07 17 50.1 | 24.66 | 0.13 | ... | ... | ... | 15.91 | 12.89 | 11.01 |
| 1487-80L | 18 38 00.49 | −06 26 46.1 | 25.67 | 0.03 | ... | ... | ... | 15.63 | 13.02 | 11.29 |
| 1483-212L | 18 38 27.16 | −07 10 45.0 | 25.07 | −0.40 | ... | ... | ... | 13.64 | 11.73 | 10.59 |
| 1489-36L | 18 38 38.94 | −06 00 16.0 | 26.13 | 0.10 | ... | ... | ... | 14.78 | 13.04 | 11.15 |
| 1493-9L | 18 39 34.58 | −05 44 23.2 | 26.47 | 0.01 | 18.36 | ... | 16.96 | 11.83 | 10.49 | 9.56 |
| 1487-212L | 18 39 42.53 | −06 41 46.4 | 25.64 | −0.46 | ... | ... | ... | 13.27 | 11.50 | 10.50 |
| 1495-32L | 18 41 23.36 | −05 40 58.1 | 26.73 | −0.36 | 17.97 | 17.39 | 16.16 | 12.35 | 11.15 | 10.25 |
| 1503-160L | 18 41 34.06 | −05 04 01.4 | 27.30 | −0.12 | 19.18 | ... | 15.71 | 10.22 | 9.21 | 8.51 |
| 1513-111L | 18 43 17.27 | −03 20 23.6 | 29.03 | 0.29 | ... | ... | ... | 16.17 | 14.09 | 12.04 |
| 1522-55L | 18 43 39.65 | −02 29 35.9 | 29.83 | 0.59 | ... | ... | ... | 13.41 | 12.24 | 11.47 |
| 1517-138L | 18 43 58.03 | −02 45 17.1 | 29.63 | 0.40 | 17.96 | 16.25 | 14.30 | 10.00 | 9.16 | 8.53 |
| 1527-13L | 18 47 38.33 | −02 06 38.9 | 30.62 | −0.12 | ... | ... | ... | 16.33 | 12.70 | 10.56 |
| 1528-15L | 18 49 32.31 | −02 24 27.0 | 30.57 | −0.68 | ... | ... | ... | 14.13 | 12.13 | 10.66 |
| 1536-180L | 18 51 10.77 | −01 30 03.4 | 31.57 | −0.63 | 17.26 | 15.51 | 14.58 | 10.42 | 9.76 | 9.34 |
| 1551-19L | 18 52 32.97 | +00 14 26.8 | 33.27 | −0.14 | ... | ... | ... | 16.91 | 13.62 | 11.78 |
| 1563-66L | 18 55 44.44 | +01 36 43.9 | 34.86 | −0.22 | ... | ... | ... | 16.56 | 13.29 | 11.45 |
| 1563-89L | 18 56 02.04 | +01 36 32.9 | 34.89 | −0.29 | ... | ... | ... | 17.13 | 14.32 | 12.55 |
| 1567-51L | 18 56 07.90 | +02 20 49.0 | 35.56 | 0.03 | ... | ... | ... | 14.72 | 12.27 | 10.87 |
| 1583-64L | 19 00 59.99 | +03 55 35.6 | 37.52 | −0.33 | ... | ... | ... | 17.49 | 14.80 | 12.79 |
| 1583-48L | 19 01 26.62 | +03 51 55.5 | 37.51 | −0.46 | ... | ... | ... | 14.70 | 12.67 | 11.25 |
| 1583-47L | 19 01 27.11 | +03 51 54.4 | 37.51 | −0.46 | ... | ... | ... | 14.25 | 12.27 | 10.99 |
| 1603-75L | 19 04 33.49 | +06 05 18.5 | 39.84 | −0.13 | ... | ... | ... | 16.31 | 14.38 | 13.68 |
| 1650-96L | 19 13 24.01 | +11 43 24.3 | 45.85 | 0.53 | ... | ... | ... | 8.61 | 7.99 | 7.80 |
| 1657-51L | 19 16 18.38 | +12 46 49.2 | 47.12 | 0.39 | ... | ... | ... | 12.96 | 11.82 | 10.77 |

**Table 2**
(Continued)

| Name (1) | $\alpha$(J2000) (2) | $\delta$(J2000) (3) | $l$ (4) | $b$ (5) | $B$[a] (6) | $V$[a] (7) | $R$[a] (8) | $J$[a] (9) | $H$[a] (10) | $K_s$[a] (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1670-57L | 19 17 32.79 | +14 08 27.9 | 48.46 | 0.76 | ... | ... | 19.93 | 13.90 | 12.72 | 11.67 |
| 1652-24L | 19 17 41.21 | +11 29 18.9 | 46.13 | −0.51 | ... | ... | ... | 15.29 | 13.00 | 11.53 |
| 1669-24L | 19 18 31.71 | +13 43 17.9 | 48.20 | 0.36 | ... | ... | ... | 14.35 | 12.59 | 11.33 |
| 1675-17L | 19 22 53.61 | +14 08 50.0 | 49.07 | −0.38 | ... | ... | ... | 12.67 | 10.91 | 9.68 |
| 1675-10L | 19 22 54.45 | +14 11 27.9 | 49.11 | −0.36 | ... | ... | ... | 12.83 | 11.02 | 9.58 |
| 1698-70L | 19 24 46.90 | +17 14 25.0 | 52.01 | 0.68 | ... | ... | ... | 12.65 | 11.19 | 10.25 |

**Note.** [a] The $B$, $V$, and $R$ photometry comes from the NOMAD catalog, while $J$, $H$, and $K_s$ photometry comes from 2MASS.

**Table 3**
Known W-R Stars

| Name (1) | Subtype[a] (2) | $A_{\frac{J-K_s}{K_s}}$[b] (3) | $A_{\frac{H-K_s}{K_s}}$[b] (4) | $A_{K_s}$ (5) | $K_s$ (6) | $M_{K_s}$[c] (7) | DM (8) | $d$[d] (9) | $R_G$[d] (10) |
|---|---|---|---|---|---|---|---|---|---|
| 1059-62L | WC8: | 2.06 | 1.59 | 1.82 | 11.54 | −4.65 | 14.36 | 7.46 | 4.01 |
| 1081-76L | WC8 | 1.42 | 1.19 | 1.31 | 10.73 | −4.65 | 14.07 | 6.53 | 3.81 |
| 1093-87L | WC8: | 2.55 | 2.10 | 2.33 | 11.32 | −4.65 | 13.64 | 5.36 | 4.20 |
| 1093-80L | WC8 | 2.15 | 1.85 | 2.00 | 11.47 | −4.65 | 14.12 | 6.66 | 3.60 |
| 1095-98L | WC8 | 2.04 | 1.74 | 1.89 | 11.43 | −4.65 | 14.19 | 6.89 | 3.51 |
| 1218-38L | WC8 | 2.91 | 2.43 | 2.67 | 10.33 | −4.65 | 12.31 | 2.89 | 5.65 |
| 1385-9L | WC8 | 1.48 | 1.37 | 1.42 | 8.57 | −4.65 | 11.80 | 2.29 | 6.29 |
| 1425-15L | WC6: | 0.97 | 0.79 | 0.88 | 8.27 | −4.59 | 11.97 | 2.48 | 6.19 |
| 1428-157L | WN6 | 0.66 | 0.53 | 0.59 | 8.96 | −4.41 | 12.78 | 3.59 | 5.21 |
| 1505-86L | WC7: | 2.01 | 1.37 | 1.69 | 11.99 | −4.59 | 14.89 | 9.52 | 4.51 |
| 1613-50L | WC4:: | ... | ... | ... | 11.61 | ... | ... | ... | ... |
| 1671-32L | WC7: | 1.47 | 0.84 | 1.15 | 10.76 | −4.59 | 14.20 | 6.91 | 6.50 |

**Notes.**
[a] Differences among stars of type WC4-8 are difficult to distinguish from one another. A colon (:) indicates an uncertainty of up to ±2 subtypes.
[b] Extinction was calculated from 2MASS colors and subtype values provided in Crowther et al. (2006).
[c] $M_{K_s}$ values are derived for spectral subtypes by Crowther et al. (2006).
[d] Distances ($d$) and Galactocentric radius ($R_G$) reported in kiloparsecs with typical uncertainties of 25%.

nearby line pairs as in Crowther et al. (2006). Ideally one should obtain EWs of the spectral lines, although in many cases this will be difficult, due to heavy blending for which the eye can readily compensate. The numbers and subtypes of new W-R stars found are WN5 2; WN6 6; WN7 5; WN8 3; WN9 1, for a total of 17 WN stars and WC6 4 WC7 15; WC8 and WC8-9 22; WC9 13; for a total of 54 WC stars. The grand total is 71 new W-R stars, with 24% WN and 76% WC.

It should be noted that the spectral differences among stars of type WC4-8 are subtle, and that uncertainties of one or even two subtypes are indicated by a colon in Tables 1–8.

In Figure 1, our 71 new W-R stars (in bold) have been plotted together with 321 previously known W-Rs onto the plane of the Galaxy. The distances to the other stars with established distances were taken from discovery papers and the seventh W-R catalog (Hadfield et al. 2007; Mauerhan et al. 2009, 2010a, 2010b, 2010c, 2011; Shara et al. 1999, 2009; van der Hucht 2001). The Galactic center (GC) is labeled, and circles of radius 4, 8, and 12 kpc are plotted. The Sun is indicated with a five-point star. The 71 new W-R stars are located at significantly larger heliocentric distances than most other known stars. We also find a few new stars without optical counterparts within just a few kpc of our Sun, reinforcing the necessity of W-R surveys in the near-infrared. Conti & Vacca (1990), along with the more recent re-analysis in Hadfield et al. (2007), maintain that W-R stars trace the spiral structure of the Galaxy. One arm may be seen along roughly the 8 kpc radius, and an inner arm can perhaps begin to be traced along the inner 4 kpc radius. However, the distance error bars are not trivial, so that firm conclusions about the utility of W-R stars as spiral tracers cannot yet be drawn.

The spectra of our new W-R stars are shown in Figures 2–10. Overall, few early subtypes of either sequence (WN or WC) were seen, again as expected in the inner Galaxy for higher-than-solar $Z$. Selection bias in favor of late subtypes is unlikely to be operating, since the early subtypes are the easiest W-R stars to find. We are confident that they would have been found, given their strong He II lines (WNE stars) and strong He II and C IV lines (WCE stars). Note the contrast with the outer Galaxy, where earlier types abound, as in M33 (Neugent & Massey 2011), the Large Magellanic Cloud (LMC), and especially the Small Magellanic Cloud, where $Z$ is progressively smaller. The physical reason for this is now recognized to be due to $Z$-related opacity effects. For lower $Z$, mass-loss rates are lower and one can see deeper into hotter layers of the wind. Thus, what might be a WCL star with $Z$ at twice the solar value would instead be seen as a WCE star in the LMC (where $Z$ can be half-solar). Among the 24 WC/WO stars in the LMC, 23 are WC4 and 1 is WO4; nothing cooler is seen. Only two WC7 stars are known in M33 (Neugent & Massey 2011); all others are of earlier types. In

**Table 4**
New W-R Stars

| Name (1) | Subtype[a] (2) | $A^{J-K_s}_{K_s}$ [b] (3) | $A^{H-K_s}_{K_s}$ [b] (4) | $A_{K_s}$ (5) | $K_s$ (6) | $M_{K_s}$ [c] (7) | DM (8) | $d$ [d] (9) | $R_G$ [d] (10) |
|---|---|---|---|---|---|---|---|---|---|
| 1023-63L | WC7: | 0.76 | 0.19 | 0.48 | 14.37 | −4.59 | 18.49 | 49.80 | 42.88 |
| 1042-25L | WN8 | 1.34 | 1.20 | 1.27 | 9.88 | −5.92 | 14.53 | 8.05 | 4.34 |
| 1038-22L | WC7: | 1.08 | 0.60 | 0.84 | 9.29 | −4.59 | 13.04 | 4.05 | 5.40 |
| 1054-43L | WC9 | 2.59 | 2.30 | 2.45 | 11.53 | ... | ... | ... | ... |
| 1051-67L | WC7: | 2.01 | 1.46 | 1.73 | 11.24 | −4.59 | 14.10 | 6.61 | 4.20 |
| 1077-55L | WC6: | 1.71 | 1.06 | 1.39 | 11.97 | −4.59 | 15.18 | 10.84 | 4.82 |
| 1085-72L | WC8-9 | 1.92 | 1.41 | 1.66 | 11.21 | −4.65 | 14.20 | 6.92 | 3.63 |
| 1085-69L | WC8 | 1.88 | 2.34 | 2.11 | 11.50 | −4.65 | 14.04 | 6.44 | 3.74 |
| 1085-83L | WC8: | 2.98 | 2.34 | 2.66 | 11.83 | −4.65 | 13.82 | 5.80 | 4.00 |
| 1093-138L | WC8: | 1.89 | 1.89 | 1.89 | 12.75 | −4.65 | 15.51 | 12.65 | 5.94 |
| 1093-140LB | WN9 | 1.12 | 0.35 | 0.73 | 13.99 | −5.92 | 19.18 | 68.40 | 60.70 |
| 1093-140L | WC7: | 2.18 | 2.02 | 2.10 | 12.28 | −4.59 | 14.76 | 8.97 | 3.58 |
| 1091-46L | WC8 | 2.33 | 2.48 | 2.41 | 10.02 | −4.65 | 12.26 | 2.83 | 6.02 |
| 1093-59L | WC9+late-type spectrum | 2.62 | 2.39 | 2.51 | 11.41 | ... | ... | ... | ... |
| 1095-189L | WC7: | 0.31 | −0.56 | −0.13 | 9.35 | −4.59 | 14.06 | 6.50 | 3.63 |
| 1097-156L | WN6: | 2.08 | 1.97 | 2.03 | 10.46 | −4.41 | 12.84 | 3.71 | 5.28 |
| 1097-71L | WC9 | 2.02 | 2.59 | 2.31 | 12.04 | ... | ... | ... | ... |
| 1097-34L | WC8 | 1.86 | 1.64 | 1.75 | 10.39 | −4.65 | 13.28 | 4.54 | 4.66 |
| 1106-31L | WC9 | 0.74 | 0.73 | 0.74 | 8.93 | ... | ... | ... | ... |
| 1105-76L | WC8 | 1.91 | 1.59 | 1.75 | 11.48 | −4.65 | 14.38 | 7.51 | 3.19 |
| 1109-74L | WC7: | 3.38 | 2.32 | 2.85 | 11.25 | −4.59 | 12.99 | 3.96 | 5.03 |
| 1115-197L | WN6 | 0.83 | 0.74 | 0.79 | 9.14 | −4.41 | 12.76 | 3.57 | 5.32 |
| 1138-133L | WN6 | 1.63 | 1.51 | 1.57 | 10.95 | −4.41 | 13.79 | 5.72 | 3.55 |
| 1133-59L | WC9 | 1.64 | 2.07 | 1.85 | 12.06 | ... | ... | ... | ... |
| 1168-91L | WC7: | 1.79 | 1.83 | 1.81 | 11.84 | −4.59 | 14.62 | 8.40 | 2.14 |
| 1179-129L | WC6: | 1.22 | 0.91 | 1.07 | 12.81 | −4.59 | 16.34 | 18.52 | 10.41 |
| 1181-82L | WC8 | 1.72 | 1.53 | 1.63 | 10.98 | −4.65 | 14.00 | 6.32 | 2.70 |
| 1181-81L | WC8 | 1.41 | 1.62 | 1.52 | 10.81 | −4.65 | 13.94 | 6.15 | 2.82 |
| 1181-211L | WN7: | 0.68 | 0.43 | 0.55 | 9.49 | −4.77 | 13.71 | 5.51 | 3.34 |
| 1189-110L | WC9 | 1.69 | 1.69 | 1.69 | 11.59 | ... | ... | ... | ... |
| 1245-23L | WC9 | 3.35 | 2.86 | 3.10 | 10.76 | ... | ... | ... | ... |
| 1269-166L | WC8 | 1.70 | 1.39 | 1.54 | 10.56 | −4.65 | 13.67 | 5.41 | 3.09 |
| 1275-184L | WN8 | 2.41 | 2.25 | 2.33 | 10.17 | −5.92 | 13.76 | 5.66 | 2.85 |
| 1322-220L | WN5 | 0.90 | 0.86 | 0.88 | 10.32 | −4.41 | 13.85 | 5.88 | 2.70 |
| 1327-25L | WC9 | 1.78 | 2.24 | 2.01 | 10.89 | ... | ... | ... | ... |
| 1342-208L | WN6 | 1.17 | 1.19 | 1.18 | 9.47 | −4.41 | 12.70 | 3.47 | 5.07 |
| 1381-20L | WC9 | 2.18 | 4.26 | 3.22 | 10.75 | ... | ... | ... | ... |
| 1395-86L | WC8 | 3.89 | 3.15 | 3.52 | 11.85 | −4.65 | 12.97 | 3.94 | 4.77 |
| 1434-43L | WC8 | 1.56 | 1.51 | 1.53 | 11.69 | −4.65 | 14.81 | 9.15 | 2.99 |
| 1431-34L | WN8 | 1.42 | 1.34 | 1.38 | 9.28 | −5.92 | 13.82 | 5.82 | 3.52 |
| 1463-7L | WC8 | 1.60 | 1.43 | 1.51 | 9.36 | −4.65 | 12.50 | 3.16 | 5.72 |
| 1477-55L | WC9 | 3.13 | 2.94 | 3.03 | 11.01 | ... | ... | ... | ... |
| 1487-80L | WC9 | 2.75 | 2.68 | 2.71 | 11.29 | ... | ... | ... | ... |
| 1483-212L | WN7: | 1.80 | 1.58 | 1.69 | 10.59 | −4.77 | 13.67 | 5.42 | 4.26 |
| 1489-36L | WC9 | 2.28 | 2.97 | 2.62 | 11.15 | ... | ... | ... | ... |
| 1493-9L | WC8 | 1.23 | 1.00 | 1.12 | 9.56 | −4.65 | 13.09 | 4.14 | 5.14 |
| 1487-212L | WN7 | 1.61 | 1.32 | 1.46 | 10.50 | −4.77 | 13.81 | 5.78 | 4.13 |
| 1495-32L | WC8 | 1.12 | 0.94 | 1.03 | 10.25 | −4.65 | 13.87 | 5.94 | 4.16 |
| 1503-160L | WN7 | 0.90 | 0.78 | 0.84 | 8.51 | −4.77 | 12.44 | 3.08 | 5.93 |
| 1513-111L | WC7: | 2.35 | 2.68 | 2.52 | 12.04 | −4.59 | 14.11 | 6.63 | 4.20 |
| 1522-55L | WC9 | 1.15 | 0.92 | 1.03 | 11.47 | ... | ... | ... | ... |
| 1517-138L | WN7 | 0.74 | 0.65 | 0.69 | 8.53 | −4.77 | 12.61 | 3.33 | 5.84 |
| 1527-13L | WC8 | 3.57 | 3.19 | 3.38 | 10.56 | −4.65 | 11.83 | 2.33 | 6.61 |
| 1528-15L | WC7 | 1.91 | 1.62 | 1.76 | 10.66 | −4.59 | 13.49 | 4.99 | 4.91 |
| 1536-180L | WN5 | 0.60 | 0.46 | 0.53 | 9.34 | −4.41 | 13.22 | 4.40 | 5.28 |
| 1551-19L | WC8: | 3.15 | 2.66 | 2.90 | 11.78 | −4.65 | 13.53 | 5.08 | 5.09 |
| 1563-66L | WC8: | 3.13 | 2.65 | 2.89 | 11.45 | −4.65 | 13.21 | 4.39 | 5.50 |
| 1563-89L | WC7: | 2.66 | 2.16 | 2.41 | 12.55 | −4.59 | 14.73 | 8.83 | 5.20 |
| 1567-51L | WC7: | 2.17 | 1.49 | 1.83 | 10.87 | −4.59 | 13.63 | 5.33 | 5.19 |
| 1583-64L | WC7: | 2.74 | 2.62 | 2.68 | 12.79 | −4.59 | 14.70 | 8.70 | 5.53 |
| 1583-48L | WC8 | 2.02 | 1.89 | 1.96 | 11.25 | −4.65 | 13.95 | 6.16 | 5.21 |
| 1583-47L | WC8 | 1.89 | 1.63 | 1.76 | 10.99 | −4.65 | 13.88 | 5.96 | 5.24 |
| 1603-75L | WC8 | 1.47 | 0.58 | 1.02 | 13.68 | −4.65 | 17.31 | 28.97 | 23.09 |
| 1650-96L | WN6 | 0.42 | 0.05 | 0.23 | 7.80 | −4.41 | 11.98 | 2.49 | 7.00 |
| 1657-51L | WC7 | 1.05 | 0.86 | 0.95 | 10.77 | −4.59 | 14.40 | 7.60 | 6.49 |

**Table 4**
(Continued)

| Name (1) | Subtype[a] (2) | $A^{J-K_s}_{K_s}$ [b] (3) | $A^{H-K_s}_{K_s}$ [b] (4) | $A_{K_s}$ (5) | $K_s$ (6) | $M_{K_s}$ [c] (7) | DM (8) | $d$ [d] (9) | $R_G$ [d] (10) |
|---|---|---|---|---|---|---|---|---|---|
| 1670-57L | WC6: | 1.08 | 0.87 | 0.98 | 11.67 | −4.59 | 15.28 | 11.38 | 8.57 |
| 1652-24L | WC7: | 2.10 | 1.61 | 1.86 | 11.53 | −4.59 | 14.27 | 7.14 | 6.25 |
| 1669-24L | WC6: | 1.61 | 1.24 | 1.43 | 11.33 | −4.59 | 14.49 | 7.91 | 6.72 |
| 1675-17L | WC7: | 1.59 | 1.20 | 1.39 | 9.68 | −4.59 | 12.87 | 3.75 | 6.67 |
| 1675-10L | WC8 | 1.89 | 1.93 | 1.91 | 9.58 | −4.65 | 12.33 | 2.92 | 6.95 |
| 1698-70L | WN6 | 1.36 | 1.21 | 1.29 | 10.25 | −4.41 | 13.37 | 4.73 | 6.72 |

**Notes.**
[a] Differences among stars of type WC4-8 are difficult to distinguish from one another. A colon (:) indicates an uncertainty of ±2 subtypes.
[b] Extinction was calculated from 2MASS colors and subtype values provided in Crowther et al. (2006).
[c] $M_{K_s}$ values are derived for spectral subtypes by Crowther et al. (2006).
[d] Distances ($d$) and Galactocentric radius ($R_G$) reported in kiloparsecs with typical uncertainties of 25%.

**Table 5**
Equivalent Width (Å) Measurement for the Most Prominent Lines of the New WN Stars

| Name (1) | SpT (2) | N v 2.100 $\mu$mm (Å) (3) | He i 2.115 $\mu$mm (Å) (4) | He ii + Br $\gamma$ 2.165 $\mu$mm (Å) (5) | He ii 2.189 $\mu$mm (Å) (6) | $\frac{W_{2.189}}{W_{2.165}}$ (7) |
|---|---|---|---|---|---|---|
| 1322-220L | WN5 | −8 | −10 | −32 | −65 | 2.0 |
| 1536-180L | WN5 | −3 | −10 | −17 | −55 | 3.2 |
| 1097-156L | WN6: | ... | −62 | −67 | −108 | 1.6 |
| 1115-197L | WN6 | −3 | −27 | −38 | −68 | 1.8 |
| 1138-133L | WN6 | −2 | −29 | −9 | −104 | 11.6 |
| 1342-208L | WN6 | −4 | −41 | −13 | −72 | 5.5 |
| 1650-96L | WN6 | −5 | −37 | −49 | −52 | 1.1 |
| 1698-70L | WN6 | ... | −24 | −9 | −101 | 11.2 |
| 1181-211L | WN7: | ... | −16 | −21 | −22 | 1.0 |
| 1483-212L | WN7: | −6 | −62 | −60 | −51 | 0.9 |
| 1487-212L | WN7 | −7 | −60 | −63 | −48 | 0.8 |
| 1503-160L | WN7 | ... | −53 | −52 | −32 | 0.6 |
| 1517-138L | WN7 | −7 | −56 | −61 | −33 | 0.5 |
| 1042-25L | WN8 | −3 | −41 | −63 | −17 | 0.3 |
| 1275-184L | WN8 | −4 | −51 | −59 | −14 | 0.2 |
| 1431-34L | WN8 | −5 | −44 | −50 | −20 | 0.4 |
| 1093-140LB | WN9 | ... | −101 | −90 | ... | ... |

the Local Group, WC9 stars are only found in the inner Galaxy and possibly in the metal-richest parts of M31.

Some types may not have been found: WO (since our filters did not select for O lines) and extreme WC9d stars. Lines are severely veiled by continuum dust emission in these cooler WC types, which often show IR excesses from heated dust being formed in wind collisions with an orbiting companion. The latter might best be discovered in broadband near-IR + mid-IR surveys of the type described by Mauerhan et al. (2009) and Mauerhan et al. (2011).

## 4. DUDS

About 43% our W-R candidates turned out not to be W-R stars. All of the "duds" resembled one of the four examples we show in Figure 11. In each case, the flux of these stars is greater in one or more of our narrowband filters than in one or both of the continuum filters described in Paper I. The cause is not an emission line, but usually absorption in a continuum filter, or a steeply varying spectrum which also mimicked emission. Using broadband $J$, $H$, $K$ plus mid-IR photometry to further filter our narrowband candidates may help us avoid almost all of these duds in the future. This is because the broad color space of Mauerhan et al. (2011) returns about 95% early-type emission-line stars. Thus, the combination of broadband-IR PLUS narrowband.

## 5. THREE NOTEWORTHY STARS

Two of our new W-R stars, 1583-48L and 1583-47L, are separated by only 8 arcsec on the sky; both are of subtype WC8, and it is apparent from their finder charts (Figure 12) that they belong to a small, compact cluster.

We also note our new WC7: star 1675-17L, which is seen to have extremely bright arcs of gas emitting predominantly in the lines of He i and Br-gamma.

## 6. COMPLETENESS, SUCCESS RATE, AND COMPLEMENTARITY WITH IR-COLOR SURVEYS

Neither Paper I (41 new W-R stars) nor the present paper is a complete sample of W-R stars. We reported these 112 new W-R stars because they are exceedingly rare and interesting as potential Type Ib and Ic supernovae. They represent our increasingly successful tests of successive generations of image processing pipelines. As described in Paper I, our database of over 77,000 narrowband infrared images is far too vast to analyze in any fashion other than fully automated. The 83 W-R stars successfully picked out by our present methodology (including 71 new stars from 146 candidates) demonstrate that 57% our candidates are bona fide W-R stars. This is very encouraging, as infrared spectrographs are much less common than visible-light spectrographs (and of course all telescope time must be used with maximum efficiency). It is important to emphasize that we are reporting mostly WC stars because they are by far the strongest emission-line candidates, and we did not have enough telescope time to do a complete survey.

After this paper was completed, we became aware of an astro-ph paper (now published as Mauerhan et al. 2011), which reported 60 new W-R star discoveries via infrared color selection. Seventeen of those new W-R stars were also found in the present work, and are among the 71 new W-R stars reported in this paper. We regard the surveys as complementary. It is certainly correct that the number ratio of WC/WN in our study (54/17) is very different from that found by Mauerhan et al. (22/38). Our search area includes a part of the galaxy closer to the GC (where more WC are expected) than Mauerhan et al. appear to have searched, and we have not yet spectrographically checked the area $l$ = 284°–313° which Mauerhan et al.

**Table 6**
Equivalent Width (Å) Measurement for the Most Prominent Lines of the New WC Stars

| Name | SpT | C IV 2.076 $\mu$mm (Å) | He I + C III 2.110 $\mu$mm (Å) | He I 2.165 $\mu$mm (Å) | He II 2.189 $\mu$mm (Å) | $\frac{W_{2.076}}{W_{2.110}}$ |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| 1077-55L | WC6: | −584 | −101 | −16 | −65 | 5.8 |
| 1179-129L | WC6: | −957 | −167 | ... | ... | 5.7 |
| 1670-57L | WC6: | −969 | −128 | −25 | −89 | 7.6 |
| 1669-24L | WC6: | −190, −423 | −25, −47 | −90, −25 | −6, −56 | ... |
| 1023-63L | WC7: | −794 | −165 | −13 | −41 | 4.8 |
| 1038-22L | WC7: | −278 | −69 | −40 | −51 | 4.0 |
| 1051-67L | WC7: | −465 | −111 | ... | −20 | 4.2 |
| 1093-140L | WC7: | −372 | −62 | ... | ... | 6.0 |
| 1095-189L | WC7: | −792 | −180 | ... | ... | 4.4 |
| 1109-74L | WC7: | −300 | −33 | −5 | −55 | 9.1 |
| 1168-91L | WC7: | −544 | −88 | ... | −55 | 6.2 |
| 1513-111L | WC7: | −494 | −89 | −7 | −58 | 5.6 |
| 1528-15L | WC7 | −827 | −179 | ... | −44 | 4.6 |
| 1563-89L | WC7: | −756 | −165 | −10 | −49 | 4.6 |
| 1567-51L | WC7: | −272 | −40 | ... | −21 | 6.8 |
| 1583-64L | WC7: | −779 | −160 | ... | −82 | 4.9 |
| 1657-51L | WC7 | −530 | −86 | −13 | −48 | 6.2 |
| 1652-24L | WC7: | −690 | −88 | −20 | −68 | 7.8 |
| 1675-17L | WC7: | −680 | −111 | −33 | −66 | 6.1 |
| 1085-69L | WC8 | −146 | −111 | −17 | −26 | 1.3 |
| 1085-83L | WC8: | −321 | −100 | −28 | −32 | 3.2 |
| 1093-138L | WC8: | −557 | ... | ... | ... | ... |
| 1091-46L | WC8 | −239 | −134 | −10 | −18 | 1.8 |
| 1097-34L | WC8 | −202 | −141 | −19 | −32 | 1.4 |
| 1105-76L | WC8 | −380 | −116 | −31 | −55 | 3.3 |
| 1181-82L | WC8 | −258 | −121 | ... | −27 | 2.1 |
| 1181-81L | WC8 | −287 | −100 | −20 | −35 | 2.9 |
| 1269-166L | WC8 | −197 | −113 | −59 | −45 | 1.7 |
| 1395-86L | WC8 | −136 | −91 | −18 | −25 | 1.5 |
| 1434-43L | WC8 | −461 | −161 | −26 | −43 | 2.9 |
| 1463-7L | WC8 | −250 | −158 | −69 | −51 | 1.6 |
| 1493-9L | WC8 | −254 | −104 | −9 | −26 | 2.4 |
| 1495-32L | WC8 | −266 | −107 | −46 | −47 | 2.5 |
| 1527-13L | WC8 | −176 | −48 | −9 | −62 | 3.7 |
| 1551-19L | WC8: | −374 | −108 | ... | −25 | 3.5 |
| 1563-66L | WC8: | −284 | −82 | −25 | −25 | 3.5 |
| 1583-48L | WC8 | −412 | −158 | −30 | −53 | 2.6 |
| 1583-47L | WC8 | −297 | −107 | −15 | −33 | 2.8 |
| 1603-75L | WC8 | −370 | −132 | ... | −37 | 2.8 |
| 1675-10L | WC8 | −292 | −115 | −19 | −31 | 2.5 |
| 1085-72L | WC8-9 | −56 | −113 | −28 | −25 | 0.5 |
| 1054-43L | WC9 | ... | −82 | −70 | −12 | ... |
| 1097-71L | WC9 | −48 | −155 | −72 | −34 | 0.3 |
| 1106-31L | WC9 | −10 | −100 | −61 | −32 | 0.1 |
| 1133-59L | WC9 | −57 | −155 | −50 | −46 | 0.4 |
| 1189-110L | WC9 | −61 | −124 | −34 | −31 | 0.5 |
| 1245-23L | WC9 | −5 | −53 | −55 | −19 | 0.1 |
| 1327-25L | WC9 | −25 | −56 | −15 | −17 | 0.4 |
| 1381-20L | WC9 | −11 | −126 | −72 | −37 | 0.1 |
| 1477-55L | WC9 | −46 | −110 | −37 | −33 | 0.4 |
| 1487-80L | WC9 | −39 | −88 | −39 | −27 | 0.4 |
| 1489-36L | WC9 | −5 | −87 | −55 | −34 | 0.1 |
| 1522-55L | WC9 | −46 | −116 | −35 | −32 | 0.4 |
| 1093-59L | WC9+late-type spectrum | −81 | −66 | −9 | −18 | 1.2 |

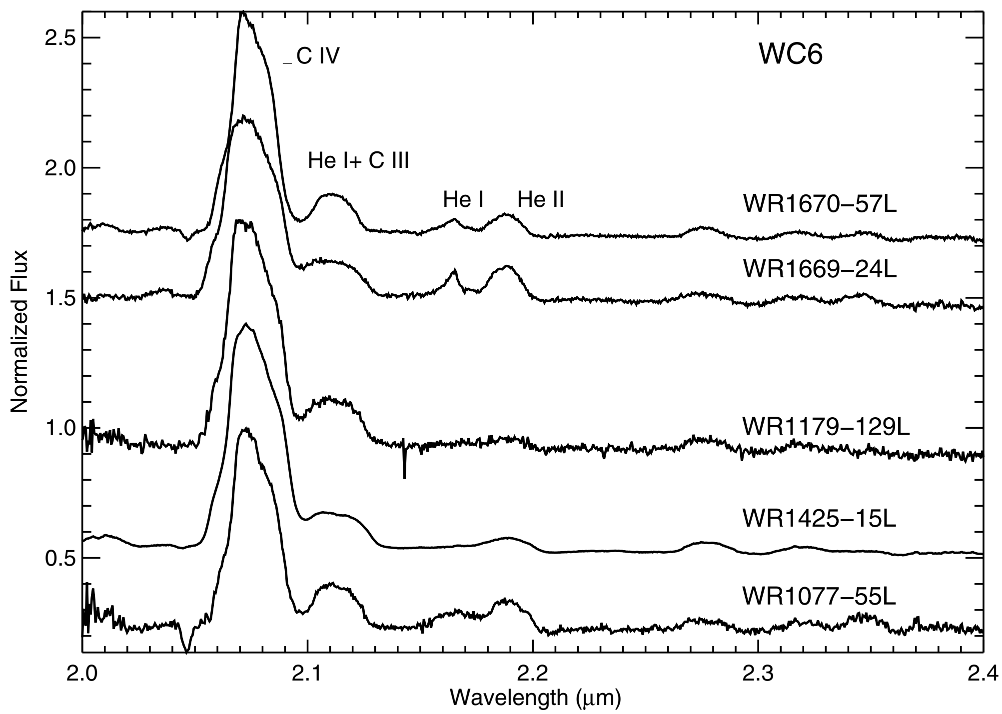


**Figure 2.** All new WC6 objects classified in this work as well as one previously identified object.

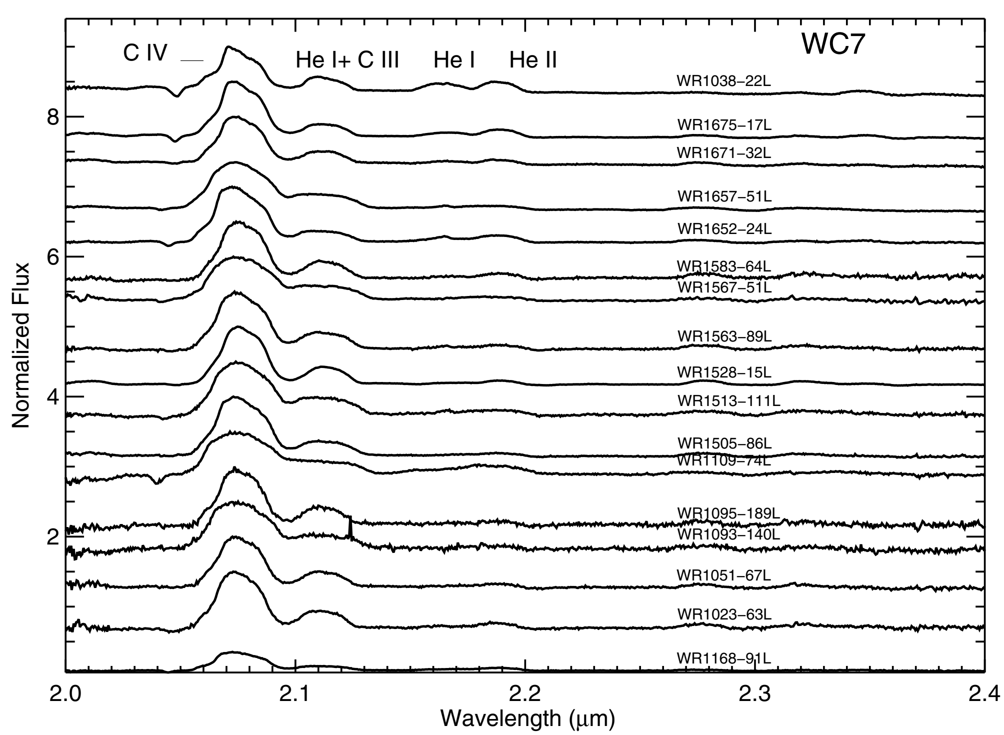


**Figure 3.** All new WC7 objects classified in this work as well as two previously identified objects.

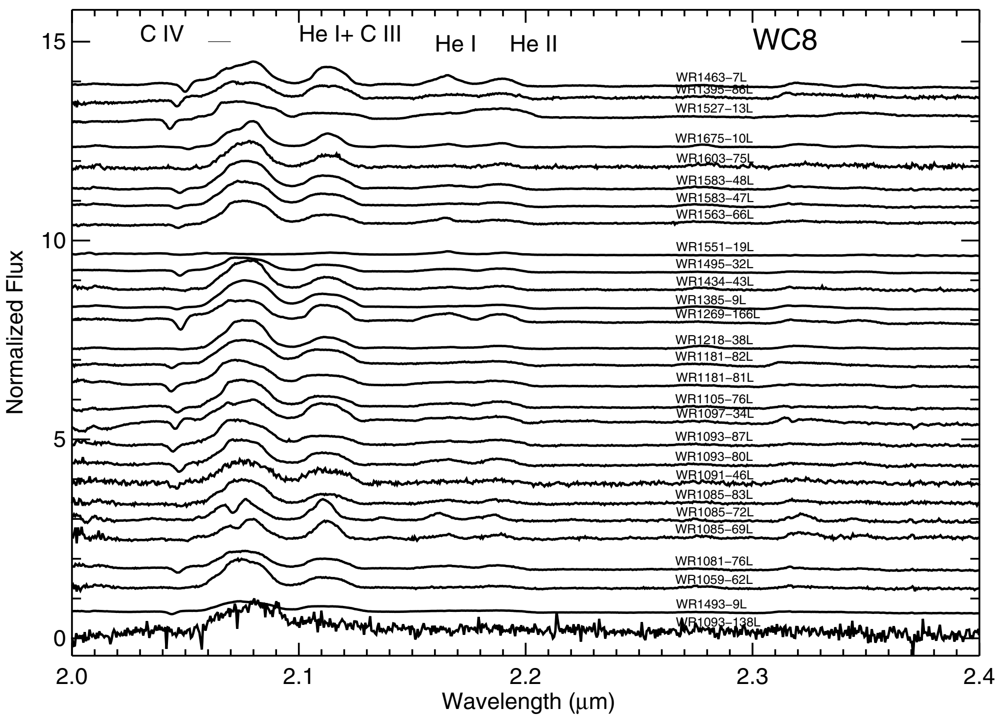


**Figure 4.** All new WC8 objects classified in this work as well as six previously identified objects.

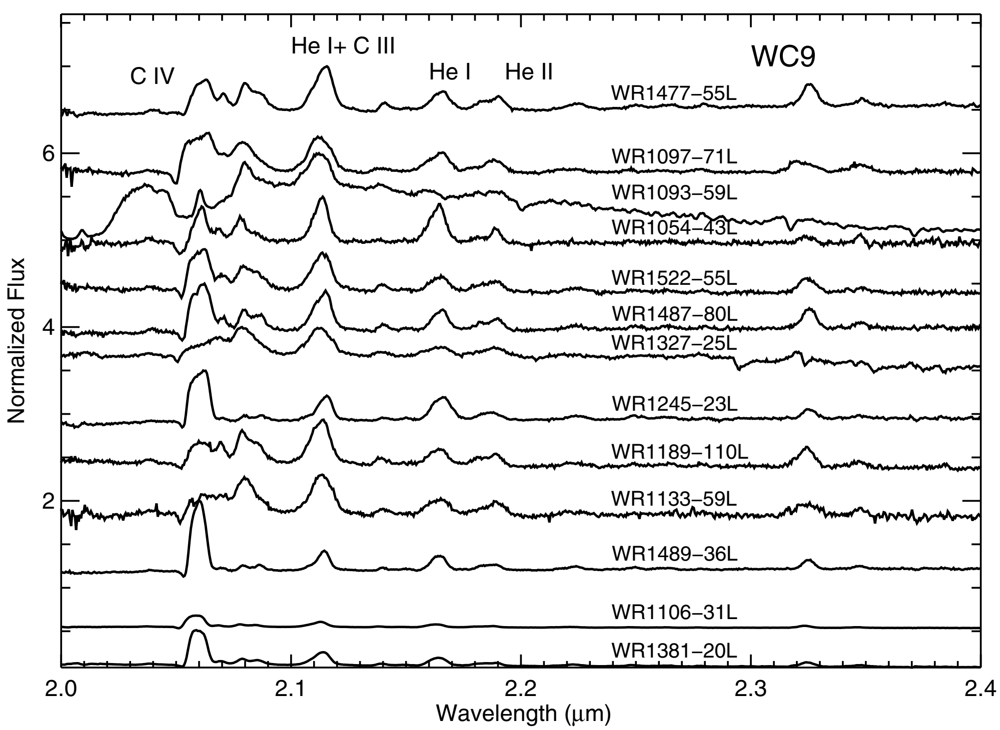


**Figure 5.** All new WC9 objects classified in this work.

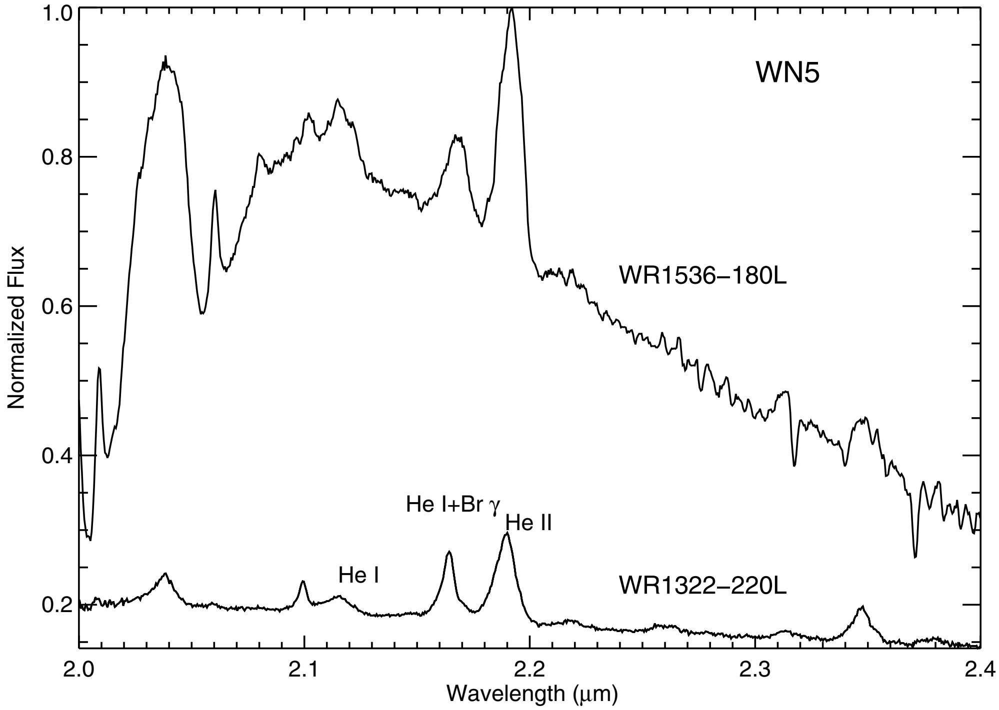


**Figure 6.** All new WN5 objects classified in this work.

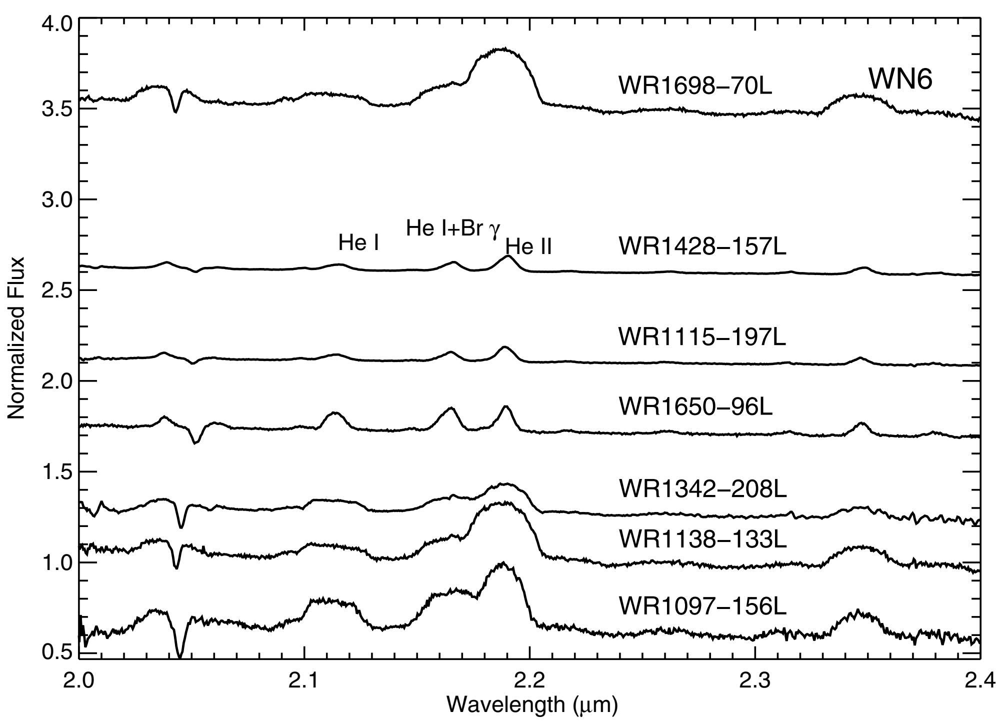


**Figure 7.** All new WN6 objects classified in this work as well as one previously identified object.

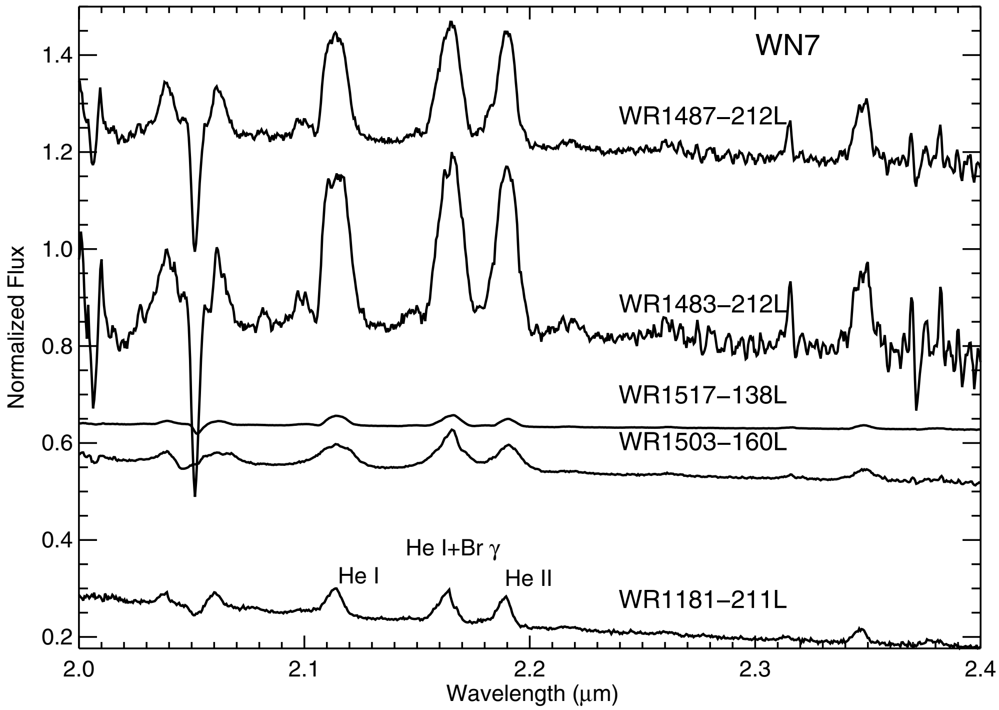


**Figure 8.** All new WN7 objects classified in this work.

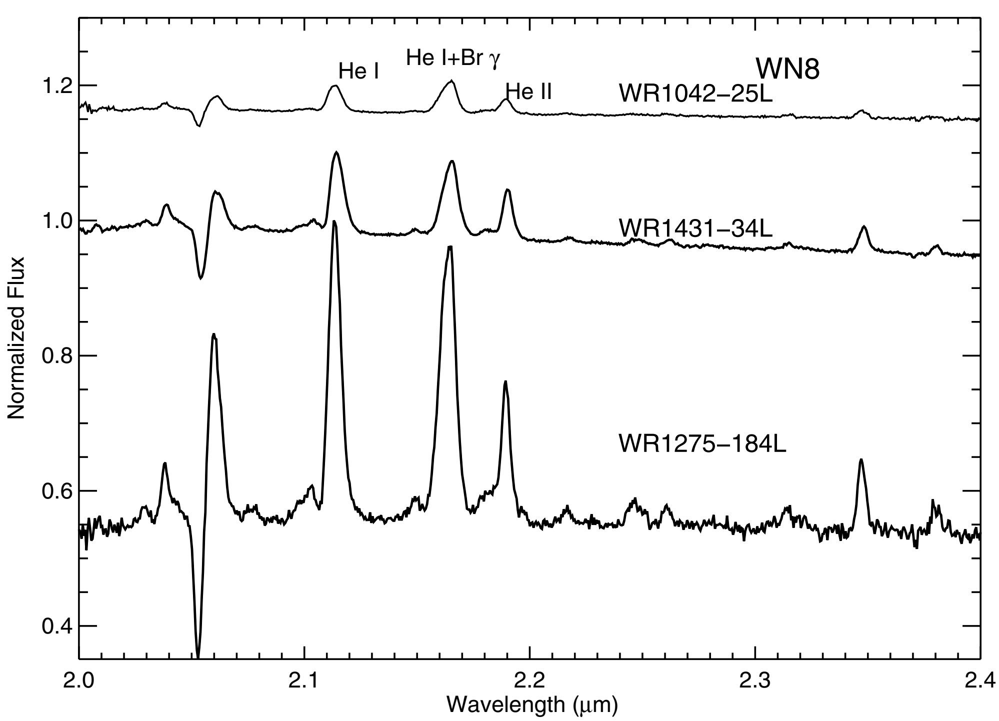


**Figure 9.** All new WN8 objects classified in this work.

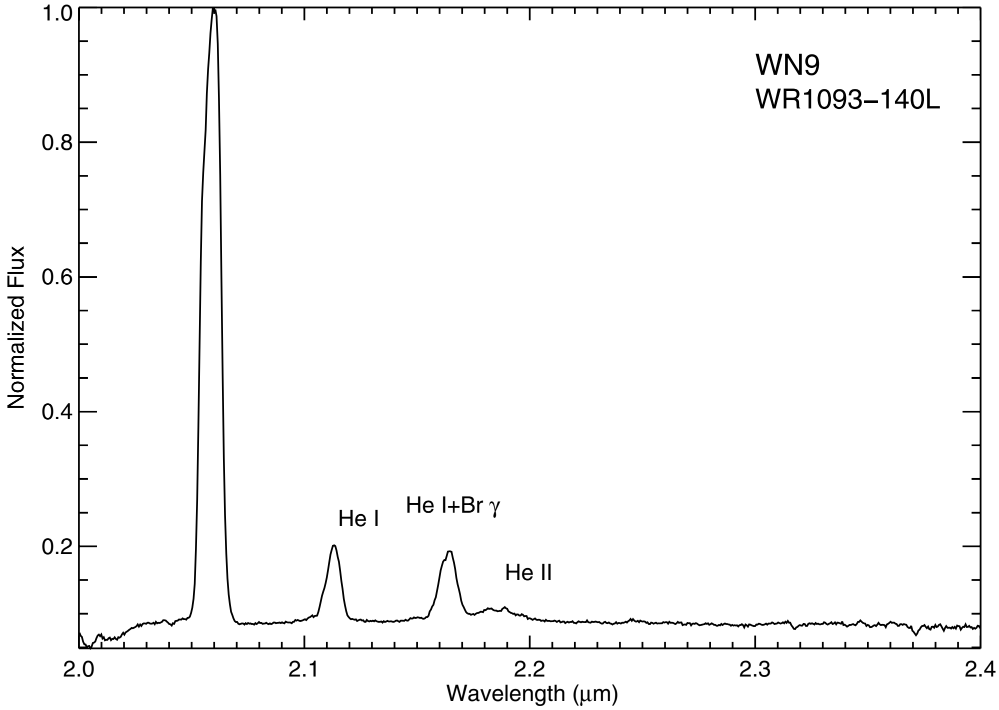


**Figure 10.** New WN9 object classified in this work.

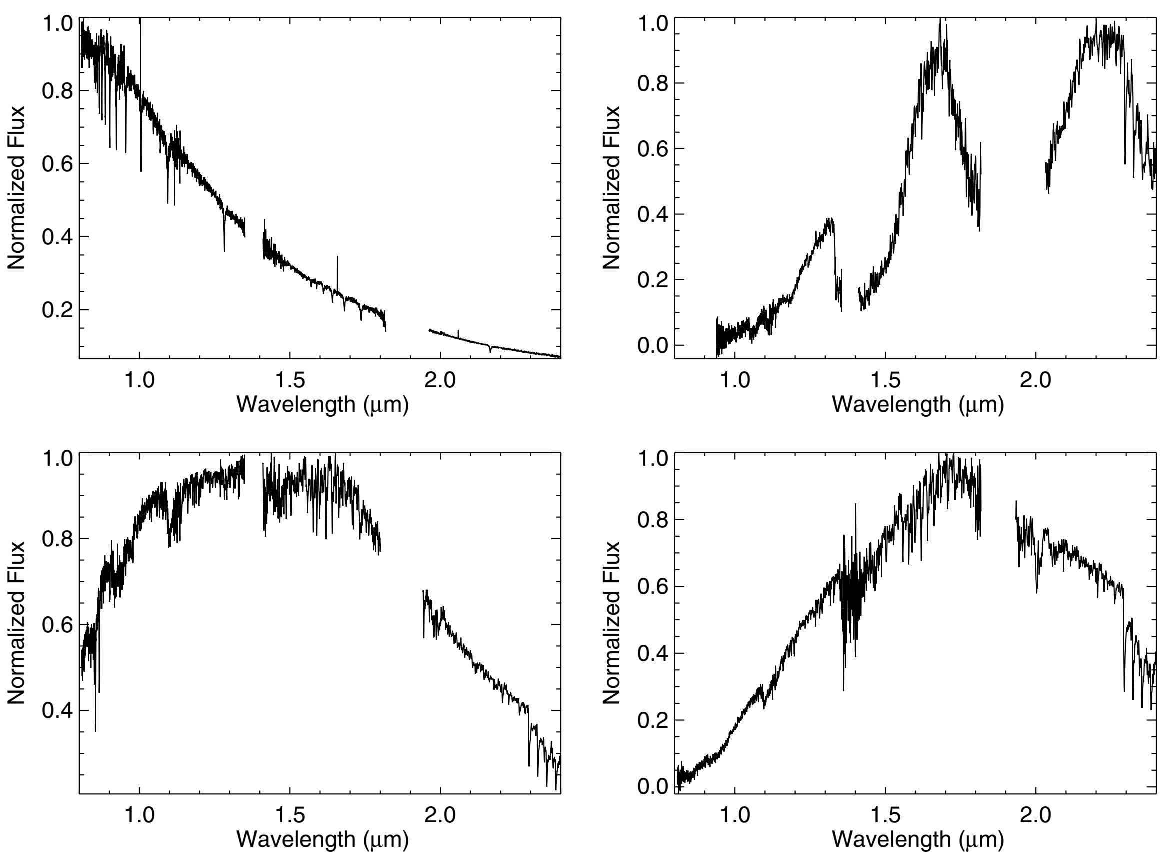


**Figure 11.** Four typical examples of objects examined in this work which did not turn out to be Wolf-Rayet stars. The upper left is a hot F- or G-type star, while the three subsequent "duds" are most likely reddened early- to late-type M giant stars.

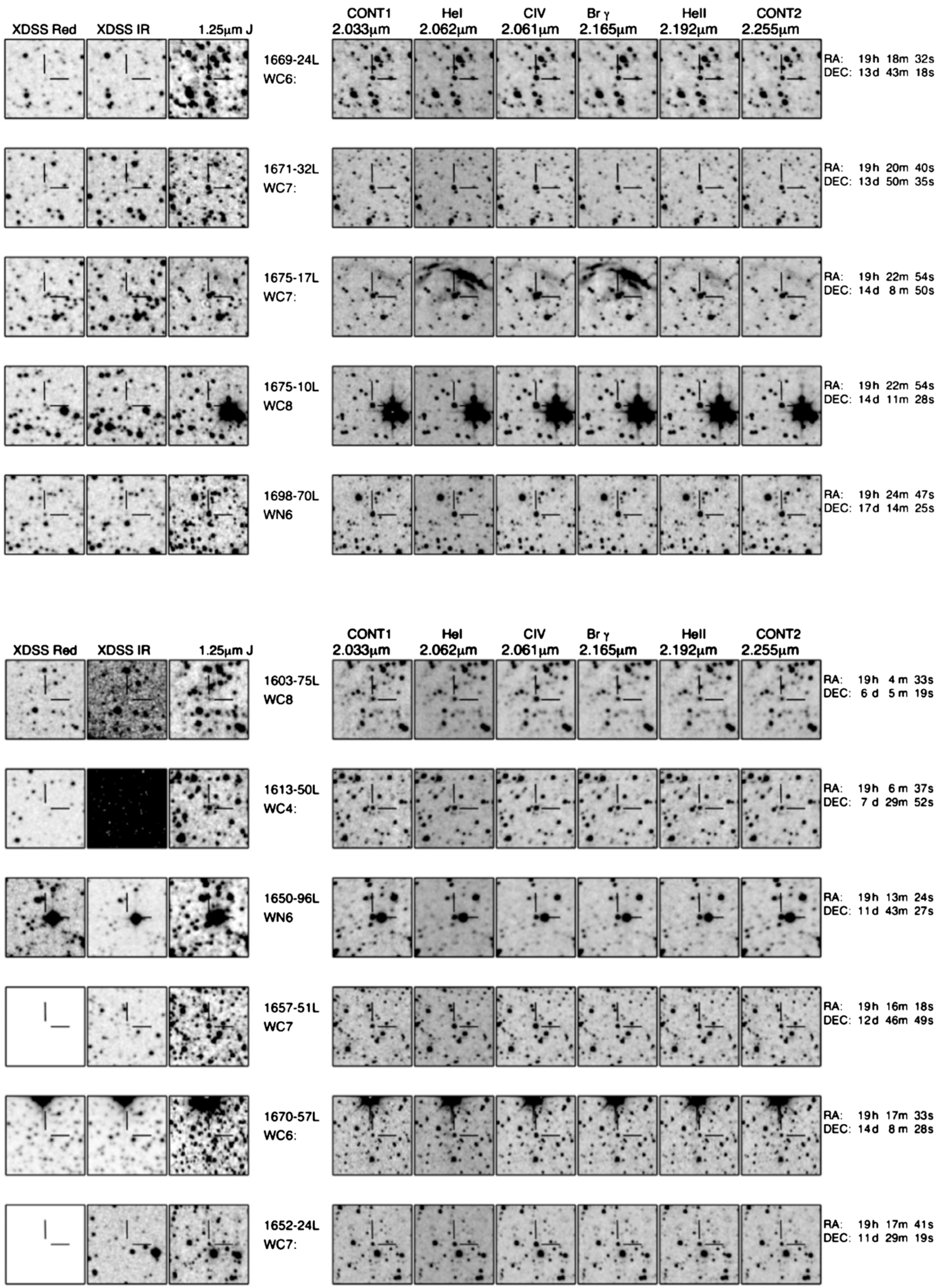


**Figure 12.** Finder charts for WC and WN stars observed with SpeX.

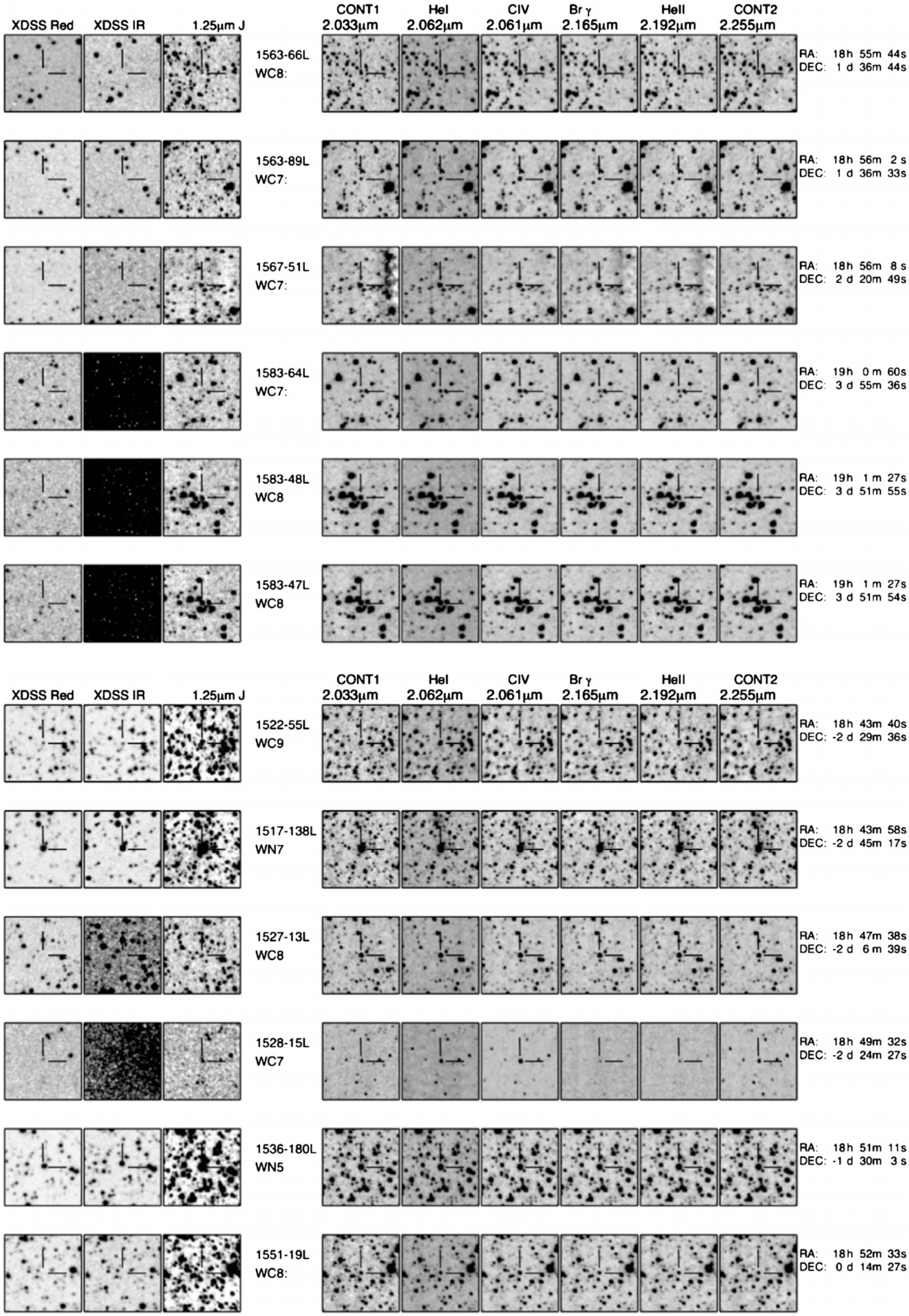


**Figure 12.** (Continued)

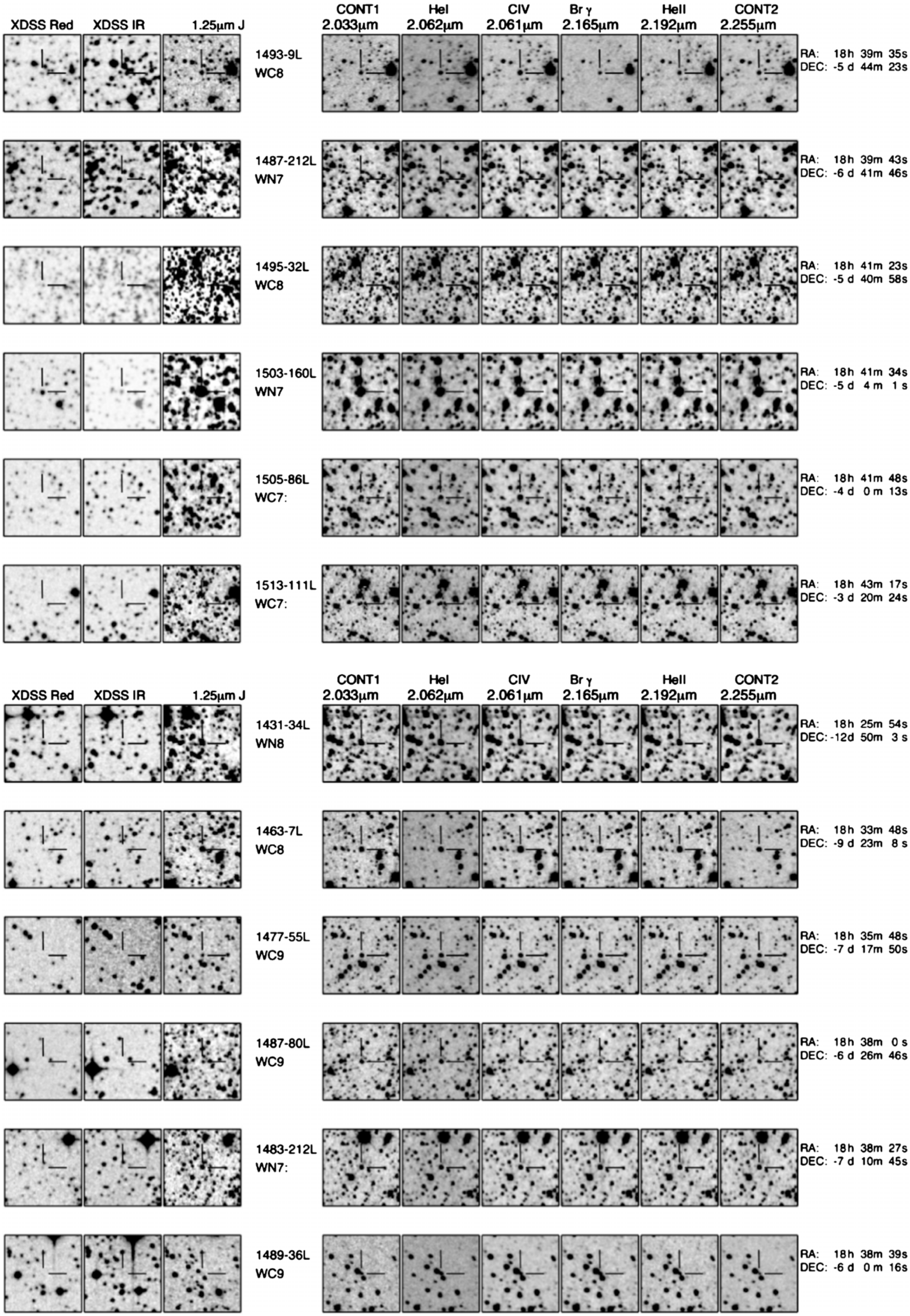


**Figure 12.** (Continued)

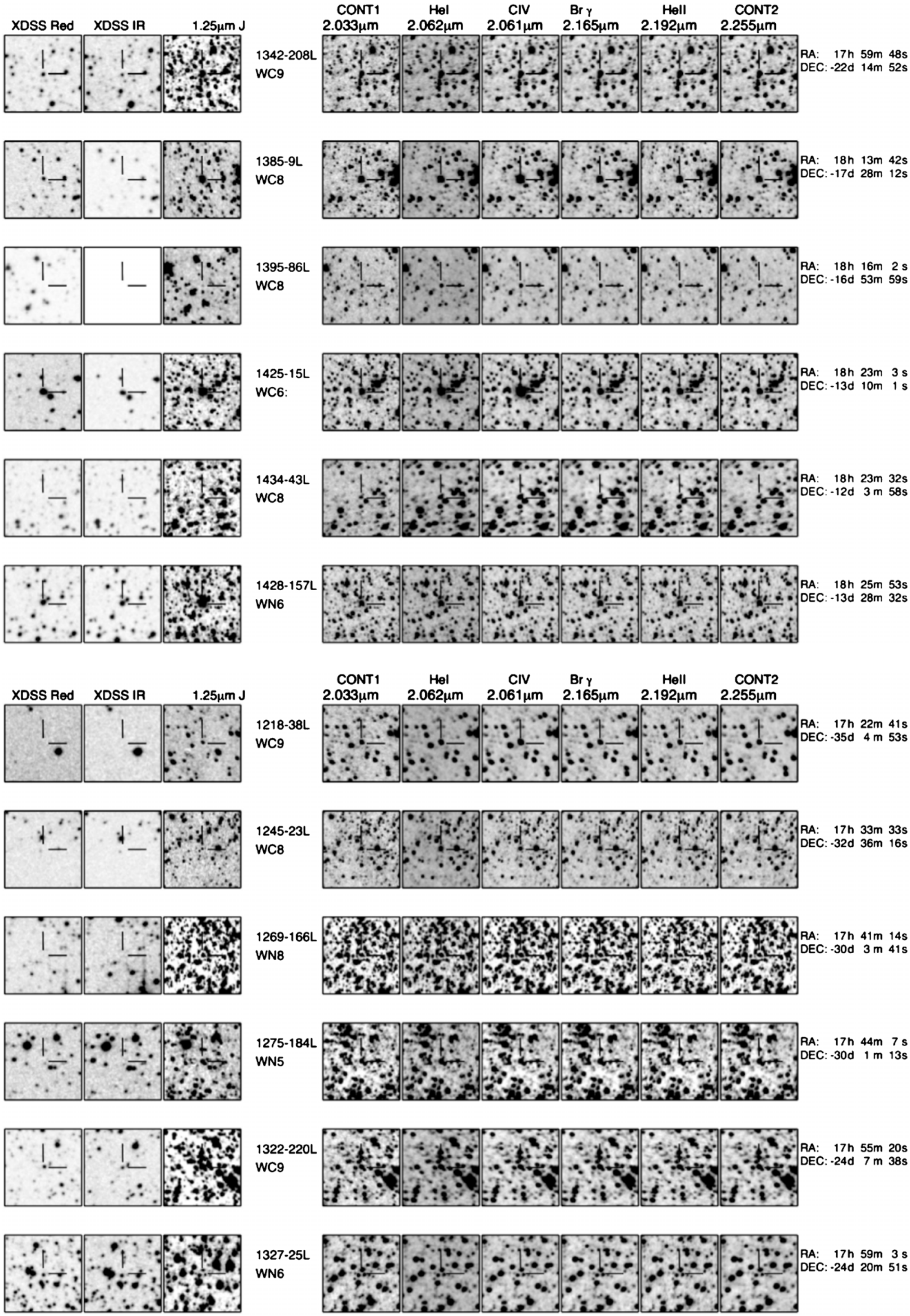


**Figure 12.** (Continued)

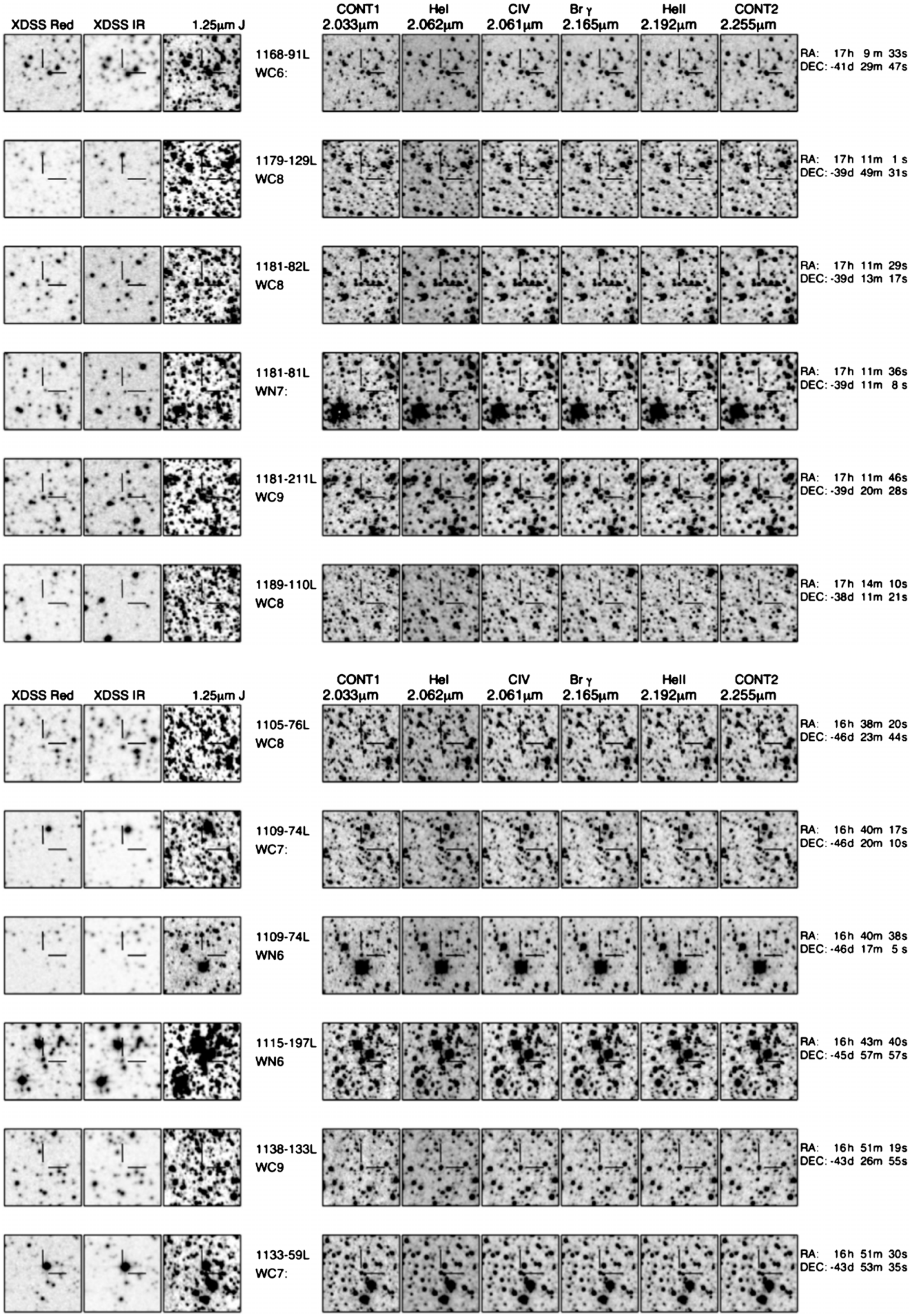


**Figure 12.** (Continued)

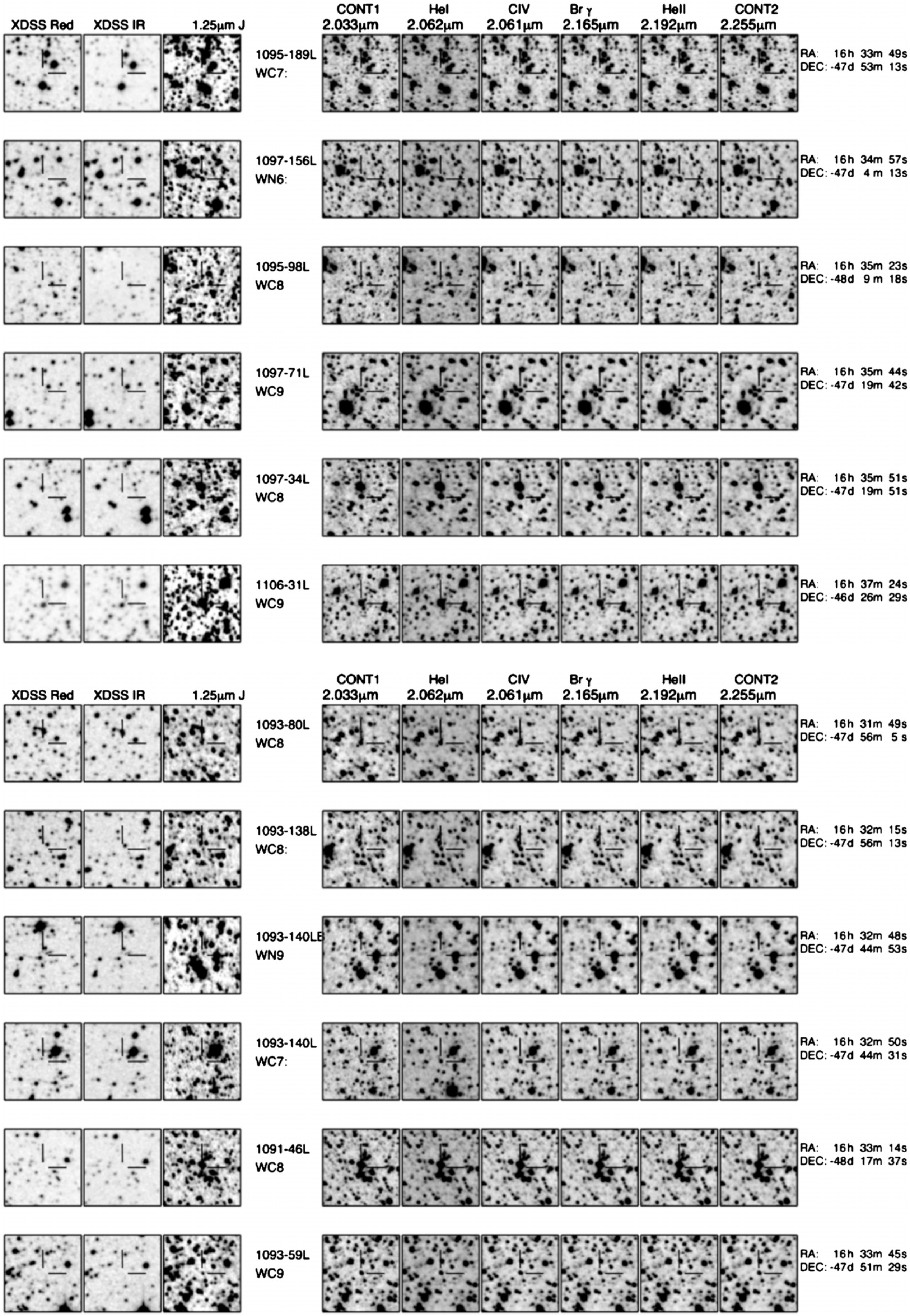


**Figure 12.** (Continued)

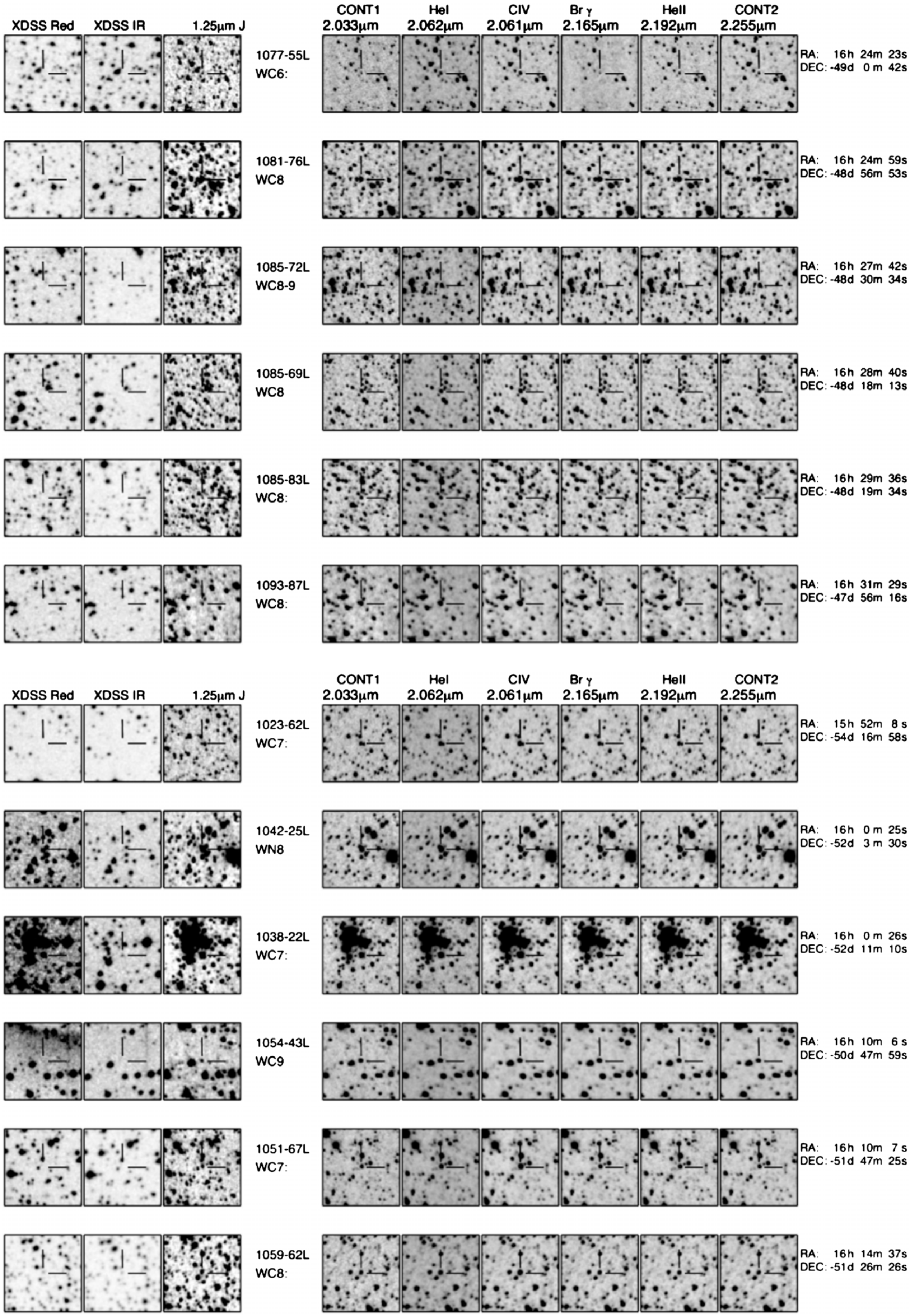


**Figure 12.** (Continued)

**Table 7**
New WC Stars Organized by Subtype

| Name (1) | Subtype (2) | $\Delta\, m_{\mathrm{He\,I}}$ (3) | $\Delta\, m_{\mathrm{C\,IV}}$ (4) | $\Delta\, m_{Br\gamma}$ (5) | $\Delta\, m_{\mathrm{He\,II}}$ (6) |
|---|---|---|---|---|---|
| 1077-55L | WC6: | 5.97 | 10.13 | 0.09 | 1.31 |
| 1179-129L | WC6: | 11.77 | 15.64 | 0.96 | 1.41 |
| 1670-57L | WC6: | 12.54 | 22.18 | 2.37 | 3.13 |
| 1669-24L | WC6: | 9.24 | 17.22 | 0.51 | 3.16 |
| 1023-63L | WC7: | ... | ... | ... | ... |
| 1038-22L | WC7: | 4.94 | 10.91 | 2.40 | 3.73 |
| 1051-67L | WC7: | 9.54 | 17.62 | −0.28 | 0.54 |
| 1093-140L | WC7: | 10.58 | 12.31 | −0.26 | 0.49 |
| 1095-189L | WC7: | 6.31 | 15.74 | 0.40 | 0.93 |
| 1109-74L | WC7: | 12.38 | 16.60 | 0.82 | 1.29 |
| 1168-91L | WC7: | 7.29 | 16.26 | 1.10 | 2.43 |
| 1513-111L | WC7: | 6.67 | 11.31 | 1.11 | 2.76 |
| 1528-15L | WC7 | 7.56 | 9.44 | 0.59 | 0.27 |
| 1563-89L | WC7: | 6.24 | 12.74 | −0.29 | 0.58 |
| 1567-51L | WC7: | 6.18 | 13.18 | −0.42 | 1.06 |
| 1583-64L | WC7: | 5.59 | 12.10 | 0.40 | 0.93 |
| 1657-51L | WC7 | 14.70 | 20.14 | 0.26 | 1.83 |
| 1652-24L | WC7: | 10.32 | 20.71 | 2.94 | 6.89 |
| 1675-17L | WC7: | 14.47 | 21.24 | 2.21 | 5.06 |
| 1085-69L | WC8 | 4.24 | 10.78 | −0.07 | 0.31 |
| 1085-83L | WC8: | 4.74 | 14.63 | 0.69 | 1.93 |
| 1093-138L | WC8: | 9.50 | 18.00 | 0.47 | 0.87 |
| 1091-46L | WC8 | 3.15 | 5.54 | 0.56 | 0.88 |
| 1097-34L | WC8 | 9.14 | 9.87 | 1.29 | 2.01 |
| 1105-76L | WC8 | 8.44 | 17.78 | 2.27 | 3.90 |
| 1181-82L | WC8 | 11.68 | 17.32 | 1.40 | 1.61 |
| 1181-81L | WC8 | 10.64 | 15.46 | 2.85 | 3.96 |
| 1269-166L | WC8 | 7.95 | 9.70 | 3.79 | 3.58 |
| 1395-86L | WC8 | 4.98 | 7.32 | 0.71 | 0.96 |
| 1434-43L | WC8 | 6.60 | 17.56 | 0.58 | 1.75 |
| 1463-7L | WC8 | 4.49 | 7.76 | 2.44 | 2.52 |
| 1493-9L | WC8 | 3.80 | 9.56 | 2.53 | 1.50 |
| 1495-32L | WC8 | 4.80 | 14.81 | 3.06 | 3.04 |
| 1527-13L | WC8 | 4.45 | 6.86 | 1.07 | 3.27 |
| 1551-19L | WC8: | 4.45 | 12.06 | 0.28 | 1.29 |
| 1563-66L | WC8: | 6.73 | 10.46 | 0.84 | 1.11 |
| 1583-48L | WC8 | 5.96 | 14.28 | 1.39 | 2.69 |
| 1583-47L | WC8 | 5.10 | 11.92 | 0.38 | 1.18 |
| 1603-75L | WC8 | 5.16 | 16.28 | 1.08 | 1.47 |
| 1675-10L | WC8 | 5.15 | 12.04 | −0.79 | 0.27 |
| 1085-72L | WC8-9 | 4.01 | 7.13 | 1.67 | 0.96 |
| 1054-43L | WC9 | 8.43 | 7.42 | 3.38 | 1.08 |
| 1097-71L | WC9 | 11.44 | 6.79 | 1.99 | 1.27 |
| 1106-31L | WC9 | 18.03 | 5.72 | 8.08 | 4.25 |
| 1133-59L | WC9 | 4.95 | 6.50 | 2.22 | 1.51 |
| 1189-110L | WC9 | 5.55 | 5.48 | 1.83 | 1.60 |
| 1245-23L | WC9 | 13.75 | 1.65 | 3.41 | 0.69 |
| 1327-25L | WC9 | ... | ... | ... | ... |
| 1381-20L | WC9 | ... | ... | ... | ... |
| 1477-55L | WC9 | 6.63 | 5.40 | 1.14 | 0.87 |
| 1487-80L | WC9 | 8.99 | 5.61 | 0.99 | 0.69 |
| 1489-36L | WC9 | 7.17 | 1.37 | 3.64 | 0.42 |
| 1522-55L | WC9 | 7.07 | 4.64 | 0.74 | 0.83 |
| 1093-59L | WC9 | 4.83 | 5.64 | −0.51 | −0.04 |

**Note.** Δ Magnitudes calculated from the narrowband images collected from our Galactic Plane Survey.

**Table 8**
New WN Stars Organized by Subtype

| Name (1) | Subtype (2) | $\Delta m_{\mathrm{He\,I}}$ (3) | $\Delta m_{\mathrm{C\,IV}}$ (4) | $\Delta m_{Br\gamma}$ (5) | $\Delta m_{\mathrm{He\,II}}$ (6) |
|---|---|---|---|---|---|
| 1322-220L | WN5 | −0.79 | −0.86 | 3.32 | 6.17 |
| 1536-180L | WN5 | −1.40 | −1.19 | 3.44 | 9.03 |
| 1097-156L | WN6: | 1.34 | 0.01 | 3.10 | 7.17 |
| 1115-197L | WN6 | −0.07 | −0.91 | 3.34 | 4.99 |
| 1138-133L | WN6 | −0.57 | −1.30 | 3.45 | 11.53 |
| 1342-208L | WN6 | −1.16 | −0.84 | 5.60 | 11.58 |
| 1650-96L | WN6 | 2.87 | 0.35 | 4.42 | 3.26 |
| 1698-70L | WN6 | −2.34 | −1.89 | 6.82 | 14.20 |
| 1181-211L | WN7: | 0.70 | −0.17 | 3.06 | 4.12 |
| 1483-212L | WN7: | 0.85 | −0.74 | 4.25 | 4.43 |
| 1487-212L | WN7 | 0.60 | 0.28 | 3.45 | 4.28 |
| 1503-160L | WN7 | 2.11 | 0.04 | 5.70 | 6.26 |
| 1517-138L | WN7 | 1.55 | −0.74 | 3.89 | 5.30 |
| 1042-25L | WN8 | 4.22 | 0.11 | 5.04 | 2.38 |
| 1275-184L | WN8 | 5.47 | −0.50 | 4.30 | 2.27 |
| 1431-34L | WN8 | 3.06 | −0.11 | 5.01 | 3.36 |
| 1093-140LB | WN9 | ... | ... | ... | ... |

**Note.** Δ Magnitudes calculated from the narrowband images collected from our Galactic Plane Survey.

did search, and where more WN are expected. This decreases the difference between our results, but only slightly. More important is the fact that WC stars are such powerful emission-line sources that they are the first candidates we have checked. This explains why we find so many more WC than WN stars. We have not yet had enough telescope time to do an area-limited, magnitude-limited, equivalent-width-limited survey in all our emission-line filters. Thus, comparisons between the color-selected and narrowband-selected methods are still premature.

## 7. FINDER CHARTS

We present in Figure 12 the finder charts for the 71 new W-R stars as well as the 11 previously identified objects described in this paper.

## 8. CONCLUSIONS

We have discovered 71 new Galactic W-R stars, 17 of type WN and 54 of type WC, via our near-infrared narrowband survey of the Galactic plane. The reduced extinction from dust and gas in the near-infrared makes this a highly effective method for future discovery of the thousands of undetected Galactic W-R stars. Of the 146 total candidates observed spectrographically, 83 proved to be new or previously identified W-R stars. With such a 57% detection rate, we have barely scratched the surface of the wealth of new W-R stars expected to be discovered within our survey area with the available data.

An initially fairly simple sky-subtraction methodology (used in Paper I) resulted in relatively scattered color–magnitude diagrams, and a detection efficiency of 24%. By raising our cut for emission objects in the study reported here to $5\sigma$, we have also increased our detection efficiency to 57%. Most of our non-detections were erroneously selected objects with almost featureless spectra and absorption bands in our continuum filters that mimicked emission lines. Improved sky subtraction (using weeks of data, median-filtered in each filter as skyflats) and including $J$, $H$, $K$ and mid-IR photometry of our candidates (the complementary method of Mauerhan et al. 2011) will allow us to further improve the detection rate of emission-line objects. We expect this survey to yield thousands of additional W-R star discoveries in the coming years.

Our survey limits will be pushed fainter by the use of still larger infrared telescopes for spectroscopic follow-up. As we increase the number of known stars, we will also increase the statistical significance of distribution plots, and subtype abundances, allowing us to learn more about our Galaxy's structure and composition. The GC is expected to prove to be an especially rich area for discovery, but it is still largely terra incognita as the crowding of stars there is very high. The large majority of Galactic W-R stars remain to be discovered, but we now have a proven and highly efficient technique to greatly extend the search.

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