Line Luminosities of Galactic and Magellanic Cloud Wolf-Rayet stars

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Abstract

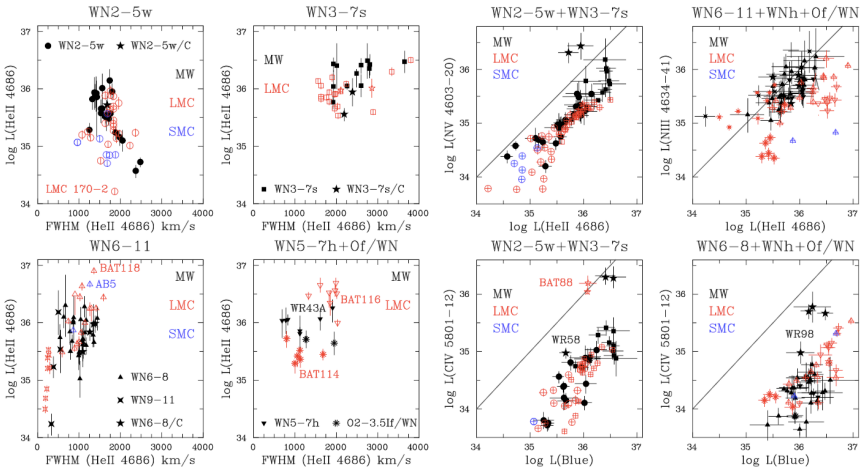
- Gaia DR3の視差と光学分光測光を使って、系内133個のWR星の輝線光度と輝線の分光テンプレートを作成。
- 低金属量環境のマゼラン銀河の112個と比較。
- 様々なタイプ、サブクラスのWR (&high mass stars) に特徴的な輝線に注目。
- 遠方のWR星への拡張。

Table 1. Source of optical spectrophotometry of Galactic and Magellanic Cloud WR stars for this study, including representative spectral resolutions at λ=5000Å.

ID	Telescope	Instrument	Epoch	Sp. Res (Å)	Wavelength Coverage (Å)	Flux Calib.	Ref	Notes
AD	ANU 2.3m	DBS	Dec 1997	5	3200–11000	10%	2	Southern WR stars, 6070–6400Å detector gap.
AR	AAT	RGO	Mar 1992–Dec 1994	2	3680–6000	10%	1	LMC/SMC WN and WN/C stars.
CS	CTIO 1.5m	SIT	Nov 1981–Feb 1985	10	3400–7270	10%	16	Southern Milky Way WR stars. Variable λ_{max}.
HF	HST	FOS	Jan 1996–Jan 1997	3	3230–6820	10%	4–6	LMC WN stars. G400 only (λ_{max}=4780Å) except for R136.
HS	HST	STIS	Mar 2014–Sep 2016	10	2900–10250	10%	17	AB5 (HD 5980).
II91	INT	IDS	Sep 1991	2	3320–7300	20%	7	Northern Milky Way WN and WN/C stars. Variable $\lambda_{min/max}$.
II96	INT	IDS	Jul 1996	3	3620–6810	10%	8	Northern Milky Way WN stars.
II13	INT	IDS	Sep 2013	5	3800–9350	20%	9	Northern Milky Way WR stars.
KI	KPNO 0.91m	IRS	Oct 1980–Feb 1983	9	3450–6900	10%	10	Northern Milky Way WR stars.
MM	Magellan	MagE	Sep 2014-Dec 2020	1.2	3170–9440	10%	13, 14	LMC WR stars.
SC	Mt Stromlo 1.9m	Coudé	Dec 1995	1	4700–6700	20%	1	LMC late-type WN stars.
WI94	WHT	ISIS	Jun 1994	3	4450–6030	10%	11	Northern Milky Way WN and WN/C stars.
WI02	WHT	ISIS	Aug 2002	3.5	3400–9500	10%	12	Northern Milky Way WC stars.
VM	VLT	MUSE	Aug 2014	3	4600–9350	10%	15	LMC WN stars. Calibration via BAT99–100 (HST/FOS).
VU	VLT	UVES	Jan 2002–Jan 2003	0.1	3200–10240	10%	18, 19	Southern Milky Way WR stars.
VX	VLT	XShooter	Nov 2011–Aug 2013	0.8	3100–24700	10%	20, 21	Southern Milky Way and LMC WR stars.

1: Crowther & Smith (1997); 2: Crowther et al. (2002), 3: Crowther & Hadfield (2006); 4: de Koter et al. (1997); 5: Massey & Hunter (1998); 6: Walborn et al. (1999); 7: Crowther et al. (1995a); 8: Crowther (1997); 9: This study; 10: Massey (1984); 11: Crowther et al. (1995c); 12: Crowther et al. (2006b); 13: Neugent et al. (2017); 14: Aadland et al. (2022b); 15: Castro et al. (2018); 16: Torres-Dodgen & Massey (1988); 17: Hillier et al. (2019); 18: Bagnulo et al. (2003); 19: Borisov et al. (2022); 20: Tramper et al. (2015); 21: Rubin-Diez et al. (in prep.);

● Observations

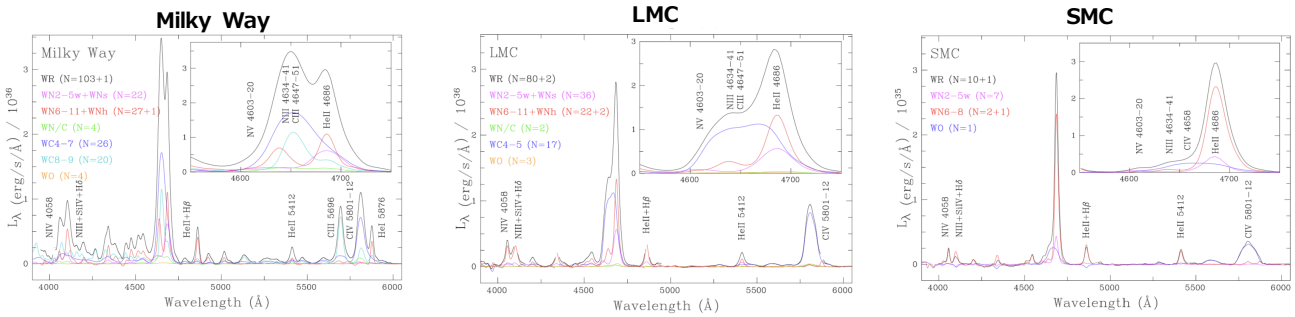


● Line ratio

- WN, WN/C, WC, WO
  : blue emission-lines（He II 4686, C III 4647/51, N III 4634/41, N v 4603/20）
  : yellow emission-lines（C IV 5801/12）
- WN＆WN/C : N IV 3478/85
- WC＆WO : O IV 3403/13
- WO : O VI 3811/34
- タイプ、サブクラス毎の FWHM(HeII 4686), L(HeII 4686), L(CIV5801/12), L(Blue)等の比

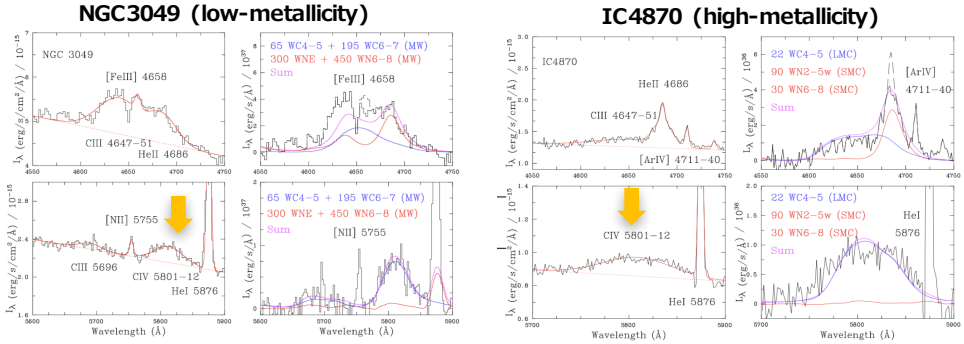
● Spectral template

・MW, LMC, SMC毎、WRタイプ毎の平均的なスペクトルテンプレート。



● Applications

・遠方に適応。
・色々な金属量環境。
・再現スペクトルで大質量星のコンポーネントを推測。



Conclusions

・early-type WN星は、低金属環境でより低い輝線強度（He II 4686とか）を示すが、late-type WN星では状況はあまり明確ではない。
・LMCのWC4-5星は銀河系の星よりも高いC IV 5801/12輝度を持つ。
・LMC/SMCの WO星の輝線輝度は銀河系の星よりも高い。
・C III 4647/51+He II 4686はすべてのWCサブタイプで強く、WC9星ではC III 5696がyellowで支配的。
・WR星のluminosityは低金属量環境ほど高くなる←→低金属量では恒星風が小さくなる←→平均的に高光度へのシフトによって打ち消される。
・LMC&SMCのblue emission C IV 5801/12のluminosityはそれぞれ2.6×10^{38} & 9×10^{36} erg/s, 8.8×10^{37} & 4×10^{36} erg/s
← MWより1桁低い。
←

Table 2. WN and Of/WN line luminosity calibrations for Milky Way, LMC and SMC stars, including He II λ4686 FWHM in km s^{-1}. The complex at λ4100 involves N III $\lambda\lambda$4097,4103, Si IV $\lambda\lambda$4088,4116, He II λ4100+Hδ, while the feature at λ4630 involves N V $\lambda\lambda$4603,20, N III $\lambda\lambda$4634,41 (or N II $\lambda\lambda$4601,43 for very late WN subtypes). Line luminosities have been adjusted for systems host to WN+WN binaries (marked with ⋄), namely WR43A, BAT99-116, BAT99-118 and AB5.

Category	N	HeII 4686 FWHM	$L_{\rm HeII4686}$ 10^{35} erg s^{-1}	$10^{-3}L_{\rm Bol}$	$\frac{L_{\rm NIV\ 3478,85}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm NIV\ 4058}}{L_{\rm HeII\ 4686}}$	$\frac{L_{4100}}{L_{\rm HeII\ 4686}}$	$\frac{L_{4630}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm HeII\ 5412}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm CIV\ 5801,12}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm HeI\ 5876}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm H\alpha}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm NIV\ 7103,29}}{L_{\rm HeII\ 4686}}$
						Milky Way ($Z_\odot$)							
WN2–5w	22	1680±310	4.9± 3.7	0.37±0.23	0.68±0.21	0.26±0.14	0.27±0.14	0.29±0.15	0.12±0.03	0.06±0.05	0.03±0.02	0.20±0.08	0.21±0.15
WN3–7s	12	2480±510	20.3± 8.9	1.25±0.40	0.49±0.14	— 0.40±0.25 —		0.27±0.16	0.13±0.02	0.07±0.03	0.05±0.03	0.15±0.04	0.16±0.04
WN6–8	25	990±240	7.4± 5.0	0.44±0.20	0.30±0.16	0.18±0.09	0.65±0.28	0.86±0.44	0.11±0.04	0.03±0.02	0.32±0.31	0.51±0.43	0.12±0.10
WN9–11	4	440±100	5.1± 6.9	0.13±0.11	· · ·	0.00±0.00	6.2±10.2	3.1±3.2	0.03±0.03	0.01±0.01	9.7±18.0	45±87	0.01±0.0
WN5–7h	7⋄	1260±510	11.0± 3.8	0.15±0.04	0.37±0.39	0.18±0.07	0.54±0.23	0.58±0.32	0.06±0.01	0.03±0.02	0.05±0.02	0.64±0.13	0.09±0.01
Of/WN	2	1610±470	4.8±0.5	0.05±0.01	0.16±0.08	0.25±0.09	0.26±0.24	0.48±0.16	0.06	0.01	0.00	0.58	· · ·
						LMC ($0.4Z_\odot$)							
WN2–5w	24	1750±280	3.3± 2.6	0.21±0.14	0.79±0.19	0.10±0.11	0.13±0.12	0.19±0.12	0.11±0.03	0.04±0.03	0.00±0.01	0.22±0.06	0.08±0.04
WN3–7s	18	2170±600	10.1± 6.9	0.70±0.24	0.50±0.23	— 0.12±0.04 —		0.16±0.03	0.13±0.01	0.05±0.03	0.01±0.02	0.16±0.03	0.07±0.03
WN6–8	13⋄	1080±270	17.8±14.0	0.39±0.16	0.20±0.08	0.17±0.03	0.33±0.14	0.34±0.19	0.09±0.03	0.03±0.02	0.09±0.06	0.41±0.24	0.06±0.01
WN9–11	8	240± 40	1.6±1.1	0.09±0.07	· · ·	0.01±0.02	1.50±0.93	1.9±1.1	0.05±0.09	0.00±0.00	1.8±1.5	6.5±5.1	· · ·
WN5–7h	8⋄	1830±250	30.2±13.6	0.24±0.12	0.44±0.14	0.18±0.05	0.18±0.09	0.07±0.03	0.09±0.02	0.03±0.01	0.01±0.01	0.34±0.08	0.11±0.04
Of/WN	6	1130±300	3.7±1.9	0.05±0.02	0.30	0.22	0.00	0.18±0.12	0.02±0.02	0.04±0.04	0.00±0.00	0.59±0.13	0.11±0.05
						SMC ($0.2Z_\odot$)							
WN2–5w	9	1630±280	1.7± 1.3	0.05±0.03	0.58	0.04±0.08	0.00±0.01	0.19±0.13	0.06±0.02	0.01±0.02	0.00±0.00	0.25±0.14	0.22
WN6–8	2⋄	1060±280	15.5±11.4	0.35±0.06	0.23±0.07	0.09±0.07	0.10±0.03	0.04±0.03	0.10±0.00	0.03±0.02	0.03±0.02	0.23±0.02	0.06±0.01
All WN2–8	140⋄	1570±610	9.7±10.1	0.42±0.37	0.48±0.27	0.14±0.11	0.26±0.25	0.34±0.33	0.10±0.04	0.04±0.03	0.08±0.17	0.30±0.23	0.12±0.14
All WN9–11	12	300±120	2.8±4.1	0.10±0.07	· · ·	0.01±0.01	3.1 ±5.9	2.3±1.9	0.02±0.02	0.00±0.01	4.4±10.3	20±52	0.01±0.00
All Of/WN	8	1250±380	3.5±1.3	0.05±0.02	0.21±0.10	0.24±0.07	0.18±0.23	0.26±0.19	0.03±0.02	0.03±0.03	0.00±0.00	0.59±0.12	0.11±0.05

Table 3. WN/C line luminosity calibrations for Milky Way and LMC stars, including He II λ4686 FWHM in km s^{-1}. The complex at λ4100 involves N III $\lambda\lambda$4097,4103, Si IV $\lambda\lambda$4088,4116, He II λ4100+Hδ, while the feature at λ4603–51 involves N V $\lambda\lambda$4603,20, N III $\lambda\lambda$4634,41 and C III $\lambda\lambda$4647,51.

Category	N	HeII 4686 FWHM	$L_{\rm HeII4686}$ 10^{35} erg s^{-1}	$10^{-3}L_{\rm Bol}$	$\frac{L_{\rm NIV\ 3478-85}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm NIV\ 4058}}{L_{\rm HeII\ 4686}}$	$\frac{L_{4100}}{L_{\rm HeII\ 4686}}$	$\frac{L_{4603,51}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm HeII\ 5412}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm CIII\ 5696}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm CIV\ 5801,12}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm H\alpha}}{L_{\rm HeII\ 4686}}$	$\frac{L_{\rm NIV\ 7103,29}}{L_{\rm HeII\ 4686}}$
						3 Milky Way ($Z_\odot$) and 2 LMC ($0.4Z_\odot$)							
WNE/C	5	2240±430	7.5±2.9	0.47±0.30	0.64±0.04	0.14±0.12	0.26±0.19	1.54±1.82	0.18±0.08	0.01±0.02	1.38±1.39	0.21±0.08	0.19±0.20
						Milky Way ($Z_\odot$)							
WNL/C	4	1270±130	7.3±3.1	0.36±0.17	0.82	0.91	0.87	1.75±1.32	0.15±0.05	0.06±0.08	0.53±0.17	0.18±0.09	0.20
All WN/C	9	1810±600	7.4±2.8	0.43±0.25	0.68±0.10	0.27±0.33	0.36±0.30	1.63±1.53	0.17±0.06	0.03±0.06	1.26±1.21	0.20±0.08	0.19±0.14

Table 4. WC line luminosity calibrations for Milky Way and LMC stars, including C IV $\lambda\lambda$5801,12 FWHM in km s^{-1}. The blue feature involves C III $\lambda\lambda$4647,51, C IV λ4658 and He II λ4686, while the feature at λ6559,81 involves He II λ6560 and C II $\lambda\lambda$6559,81.

Category	N	CIV 5801,12 FWHM	$L_{\rm CIV5801.12}$ 10^{35} erg s^{-1}	$10^{-3}L_{\rm Bol}$	$\frac{L_{\rm OIV\ 3403,13}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm Blue}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm CIII\ 5696}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm HeI\ 5876}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{6559,81}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm CIII\ 6727,73}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm CIV\ 7725}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm CIII\ 9701,19}}{L_{\rm CIV\ 5801,12}}$
						Milky Way ($Z_\odot$)						
WC4–5	11	2790±630	13.3± 6.6	1.43±0.44	0.55±0.25	2.30±0.51	0.02±0.03	0.08±0.01	0.07±0.03	0.11±0.03	0.09±0.02	0.13±0.07
WC6–7	18	2180±400	15.3± 9.0	0.89±0.43	0.77±0.24	3.11±0.50	0.35±0.24	0.16±0.11	0.16±0.06	0.17±0.03	0.11±0.01	0.28±0.06
WC8–9	21	1480±140	4.1± 3.5	0.41±0.20	1.32±0.92	4.82±1.19	3.21±1.01	0.56±0.26	1.12±0.48	0.60±0.27	0.11±0.04	0.99±0.28
						LMC ($0.4Z_\odot$)						
WC4–5	18	3370±490	34.1±19.8	2.19±0.27	0.55±0.26	1.63±0.40	0.02±0.03	0.02±0.03	0.05±0.01	0.06±0.02	0.06±0.01	0.06±0.03
All WC	68	2380±850	16.4±16.2	0.98±0.68	0.79±0.53	3.12±1.48	1.09±1.54	0.26±0.28	0.45±0.56	0.26±0.27	0.08±0.03	0.34±0.38

Table 5. WO line luminosity calibrations for Milky Way, LMC and SMC stars, including C IV $\lambda\lambda$5808 FWHM in km s^{-1}. The blue feature involves C IV λ4658 and He II λ4686.

Subtype	N	CIV 5801,12 FWHM	$L_{\rm CIV\ 5801,12}$ 10^{35} erg s^{-1}	$10^{-3}L_{\rm Bol}$	$\frac{L_{\rm OIV\ 3403,13}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm OVI\ 3811,34}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm Blue}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm OV\ 5572,607}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm HeII\ 6560}}{L_{\rm CIV\ 5801,12}}$	$\frac{L_{\rm CIV\ 7725}}{L_{\rm CIV\ 5801,12}}$
						Milky Way ($Z_\odot$)				
WO2–4	4	6800±1300	3.0±3.9	0.25±0.20	1.8±0.8	8.6±12.2	1.7±1.2	0.5±0.6	0.22±0.16	0.45±0.47
						LMC ($0.4Z_\odot$)				
WO3–4	3	5300±300	9.7±6.5	1.18±0.84	1.9±2.0	2.2±3.1	0.9±0.6	0.16±0.14	0.08±0.08	0.14±0.13
						SMC ($0.2Z_\odot$)				
WO4	1	5300	32.9	0.59	1.0	0.7	0.65	0.16	0.04	0.19
All WO	8	6100±1200	9±11	0.70±0.69	1.7±1.3	5.2±8.5	1.3±1.0	0.3±0.4	0.13±0.13	0.30±0.36

APPENDIX B: TEMPLATES

Continuum subtracted WR emission line templates are provided for the Milky Way, LMC and SMC in Figs. B1–B6. Templates are degraded to a uniform spectra resolution of 10Å, and are provided from single and single+binary WR stars, since the latter are often contaminated by (Balmer) absorption lines from companion OB stars. Average velocity corrections of 284 km s^{-1} and 162 km s^{-1} have been applied for the LMC and SMC, respectively (Tully et al. 2016).

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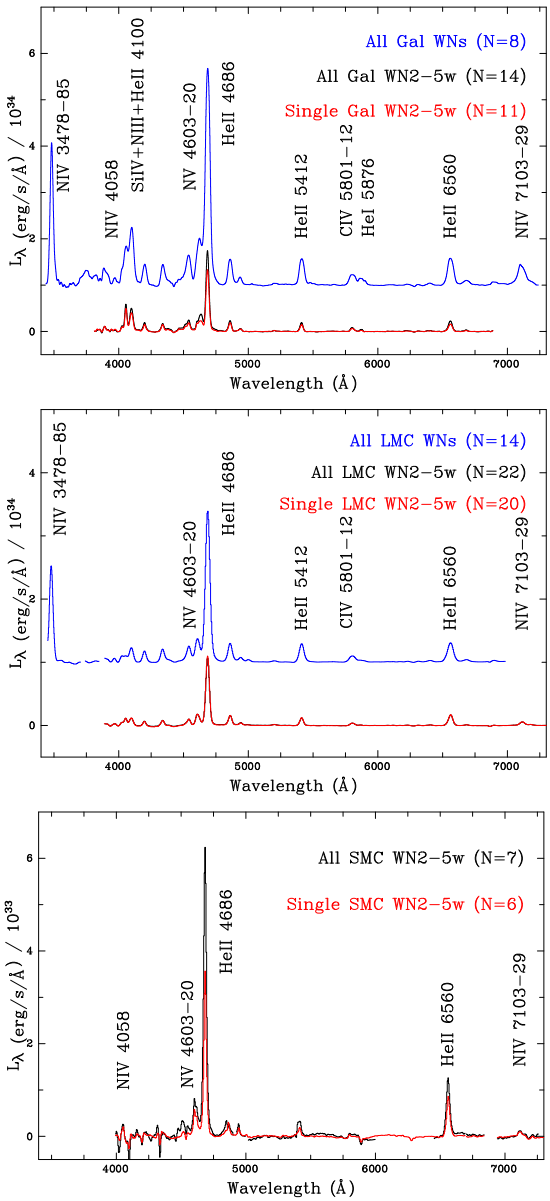

Figure B1. Upper panel: Galactic WN2–5w emission line templates based on single (red) and all (black) stars, plus WN3–7s templates (blue, offset by 10^{34} erg s^{-1} Å^{-1}); Middle panel: LMC emission line templates; Lower panel: SMC emission line templates (no strong-lined WN stars are known).

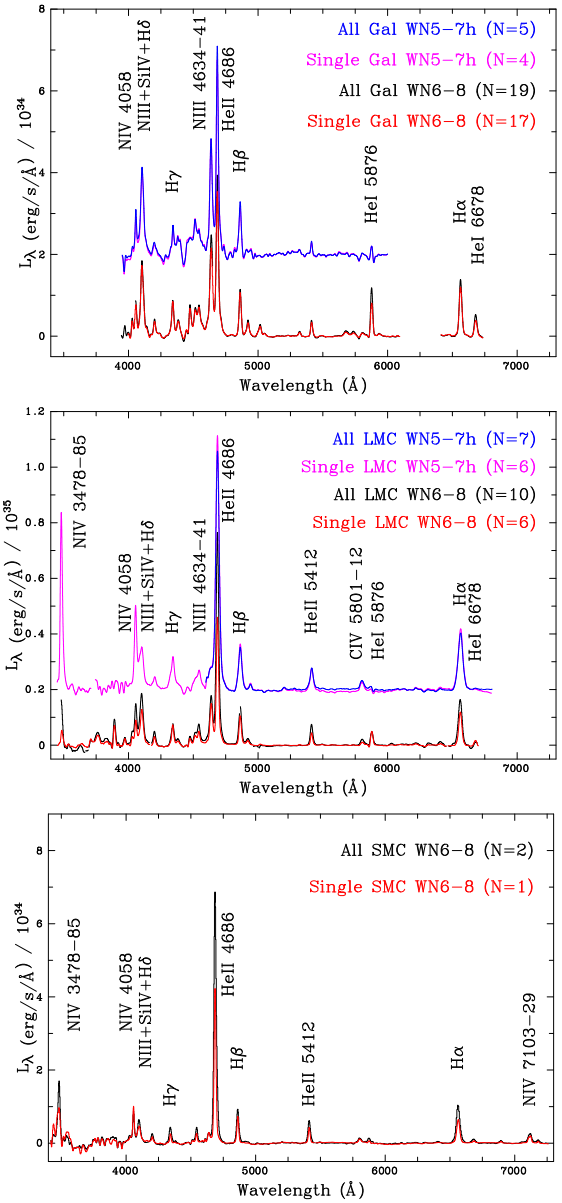

Figure B2. Upper panel: Galactic WN6–8 emission line templates based on single (red) and all (black) stars, plus WN5–7h templates (pink and blue, offset by 2×10^{34} erg s^{-1} Å^{-1}); Middle panel: LMC WN6–8 and WN5–7h emission line templates; Lower panel: SMC WN6–8 emission line templates. LMC WN5–7h templates exclude the region shortward of λ4600 owing to the use of VLT/MUSE datasets (Castro et al. 2018).

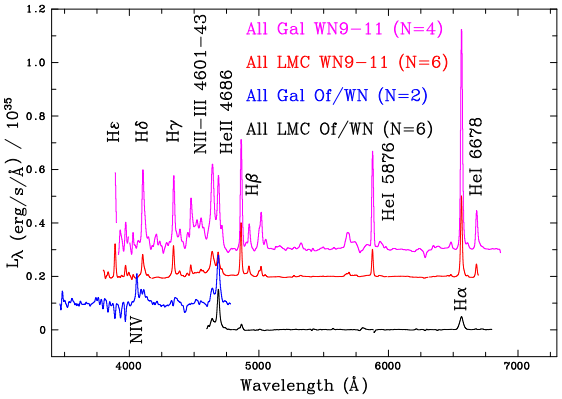

Figure B3. Emission line templates for LMC (black) and Milky Way (blue, offset by 10^{34} erg/s/Å) Of/WN stars, plus LMC (red, offset by 2×10^{34} erg s^{-1} Å^{-1}) and Milky Way (pink, offset by 3×10^{34} erg/s/Å) WN9–11 stars. LMC Of/WN templates exclude the region shortward of λ4600 owing to the use of VLT/MUSE datasets (Castro et al. 2018)

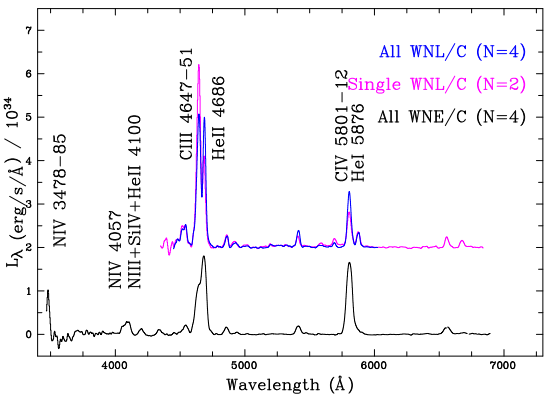

Figure B4. WN/C emission line templates for single WNE/C (black, 3 Milky Way and 2 LMC), single WNL/C (2 Milky Way, pink) and all WNL/C (4 Milky Way, blue) the latter group offset by 2×10^{34} erg s^{-1} Å^{-1}.

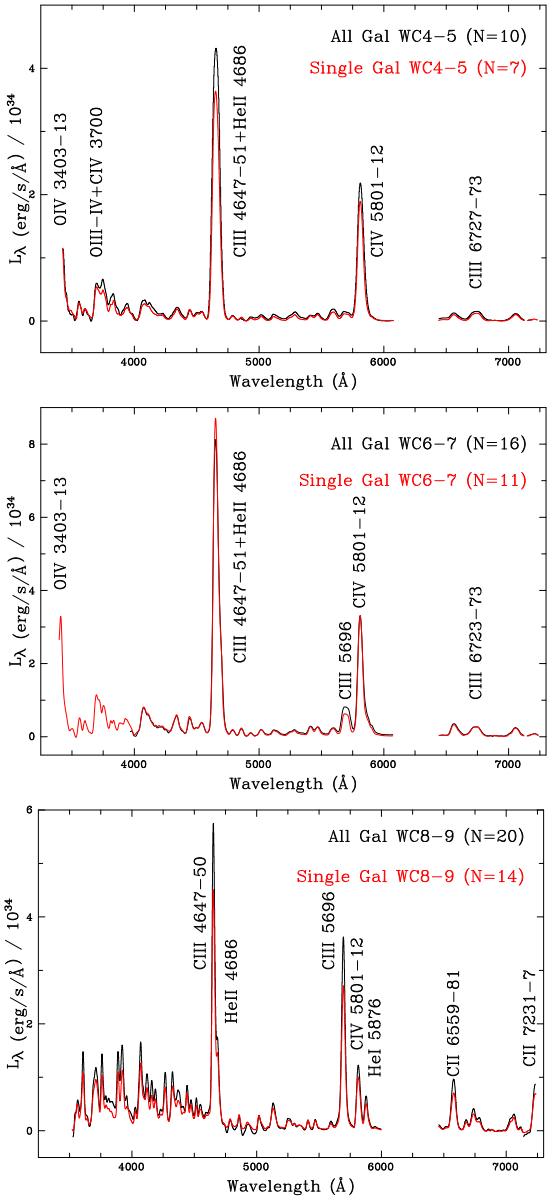

Figure B5. Upper panel: Galactic WC4–5 emission line templates based on single (red) and all (black) stars; Middle panel: Galactic WC6–7 emission line templates. Lower panel: Galactic WC8–9 emission line templates. The forest of blue features in WC8–9 stars primarily involve C II-III (Crowther et al. 2006b).

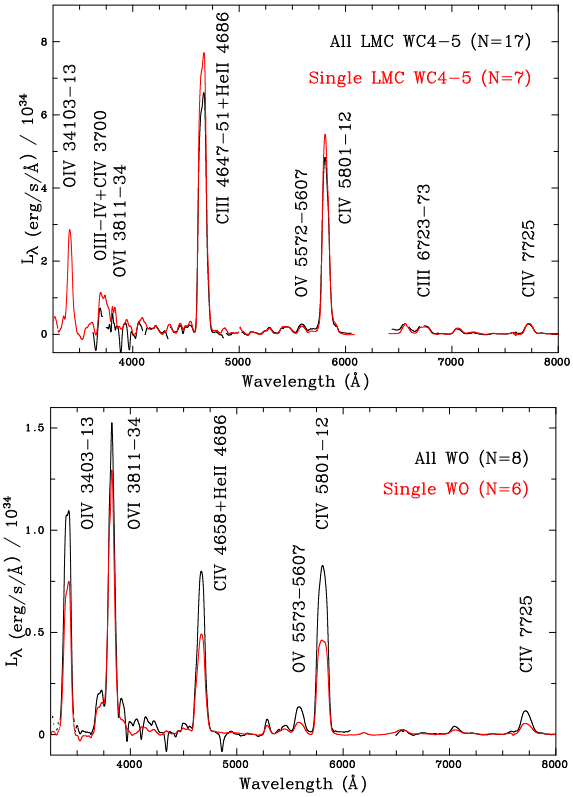

Figure B6. Upper panel: LMC WC4–5 emission line templates based on single (red) and all (black) stars; Lower panel: WO emission line templates based on single (red) and all (black) stars, incorporating all Milky Way (4), LMC (3) and SMC (1) stars.