Predicting spectra and spectral classes of chemically-homogeneously evolving stars

Brankica Kubátová & Dorottya Szécsi

Astronomický ústav AV ČR

University of Cologne

Collaborators:

Sander, A.A.C., Kubát, J., Tramper, F., Krtička, J., Kehrig, C., Hamann, W.-R., Hainich, R., Shenar, T.

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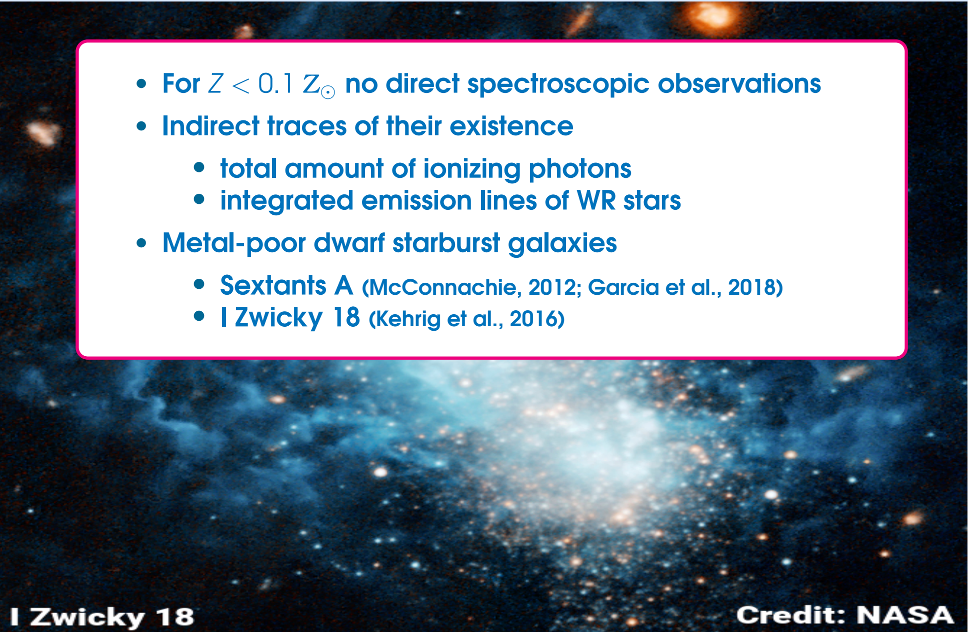
Low-metallicity massive stars

- For $Z < 0.1\,Z_\odot$ no direct spectroscopic observations
- Indirect traces of their existence
  - total amount of ionizing photons
  - integrated emission lines of WR stars
- Metal-poor dwarf starburst galaxies
  - Sextants A (McConnachie, 2012; Garcia et al., 2018)
  - I Zwicky 18 (Kehrig et al., 2016)



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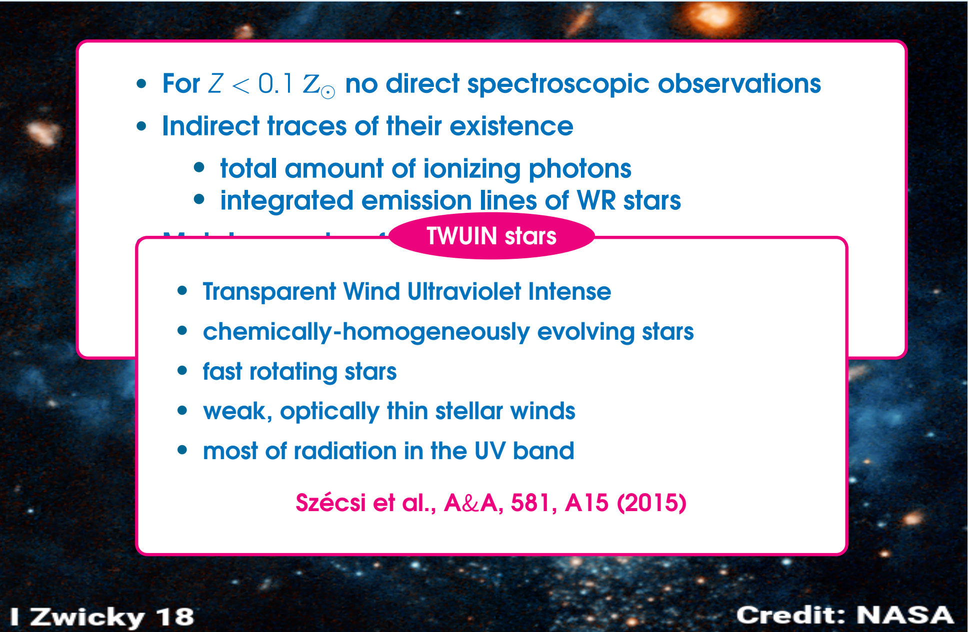
TWUIN stars

- Transparent Wind Ultraviolet Intense
- chemically-homogeneously evolving stars
- fast rotating stars
- weak, optically thin stellar winds
- most of radiation in the UV band

Szécsi et al., A&A, 581, A15 (2015)



Motivation

- Predict spectral appearance of fast rotating, chemically-homogeneously evolving stars with $Z_{\rm ini} = 0.02\,Z_\odot$ during
  - Core hydrogen-burning (CHB) phases
  - Core helium-burning (CHeB) phases
- Provide spectral features to guide targeted observing campaigns
- Create a synthetic population and calculate amount of photonionizing flux and the strength of the UV C IV stellar line
- Compare with observational properties of I Zw 18

I Zwicky 18

Credit: NASA

Calculation of the spectra

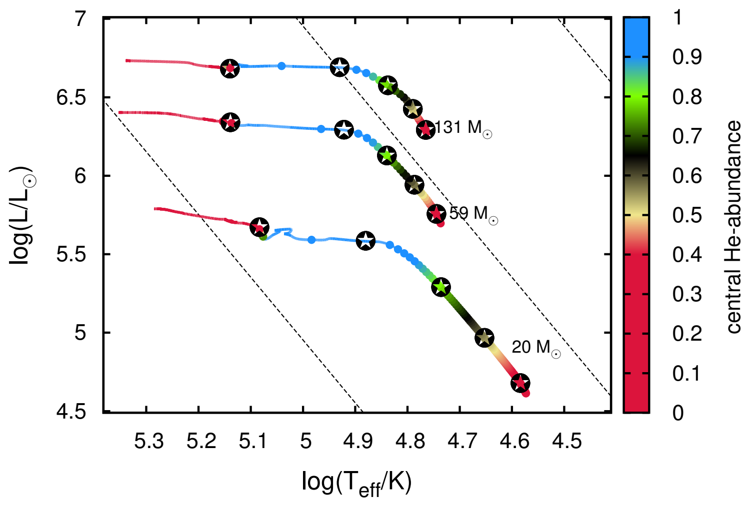
Stellar evolutionary model sequences

- Bonn evolutionary code for $Z_{\rm ini} = 0.02\, Z_\odot$ (Langer et al., 1988)
- Initial masses and rotational velocities
  - $M_{\rm ini}$=20 $M_\odot$ and $v_{\rm ini}^{\rm rot}$=450 km/s
  - $M_{\rm ini}$=59 $M_\odot$ and $v_{\rm ini}^{\rm rot}$=300 km/s
  - $M_{\rm ini}$=131 $M_\odot$ and $v_{\rm ini}^{\rm rot}$=600 km/s
- $Y_{\rm S}$ = 0.28, 0.5, 0.75, 0.98 and for CHeB phase
- Mass loss
  - $Y_{\rm S} < 0.55$ - prescription for O-type stars (Vink et al., 2000, 2001)
  - $Y_{\rm S} > 0.7$ and during the whole CHeB phase - prescription for WR stars (Hamann et al., 1995) reduction by 10 (Nugis & Lamer, 2000)

I Zwicky 18

Credit: NASA

Calculation of the spectra



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Credit: NASA

Calculation of the spectra

Stellar atmosphere and wind models

- The Potsdam Wolf-Rayet (PoWR) atmosphere code (Gräfener et al., 2002; Hamann & Gräfener, 2003, 2004; and Sander et al., 2015, 2017)
- Input from stellar evolutionary models
  - T_{eff}, L_*, M_*, and $\dot{M}$
  - Chemical compositions (mass fractions): H , He , C , N , O , Ne , Mg , Al , Si , Fe
  - Rotational velocities only for line calculations
- Additional elements ($Z_\odot$/50): P , S , Cl , Ar , K , and Ca
- Wind properties
  - β-law: β=0.8 or 1; v_∞=1000 km/s
  - Depth dependent clumping factor D

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Credit: NASA

Calculation of the spectra

Stellar atmosphere and wind models

- The Potsdam Wolf-Rayet (PoWR) atmosphere code (Gräfener et al., 2002; Hamann & Gräfener, 2003, 2004; and Sander et al., 2015, 2017)

Grid of the models

- In total 60 models
  - with nominal (higher) $\dot{M}$ and reduce $\dot{M}$ by 100
  - with smooth wind and clumped wind (D=10)
- SEDs and normalized spectra are calculated

- Wind properties
  - β-law: β=0.8 or 1; v_∞=1000 km/s
  - Depth dependent clumping factor D

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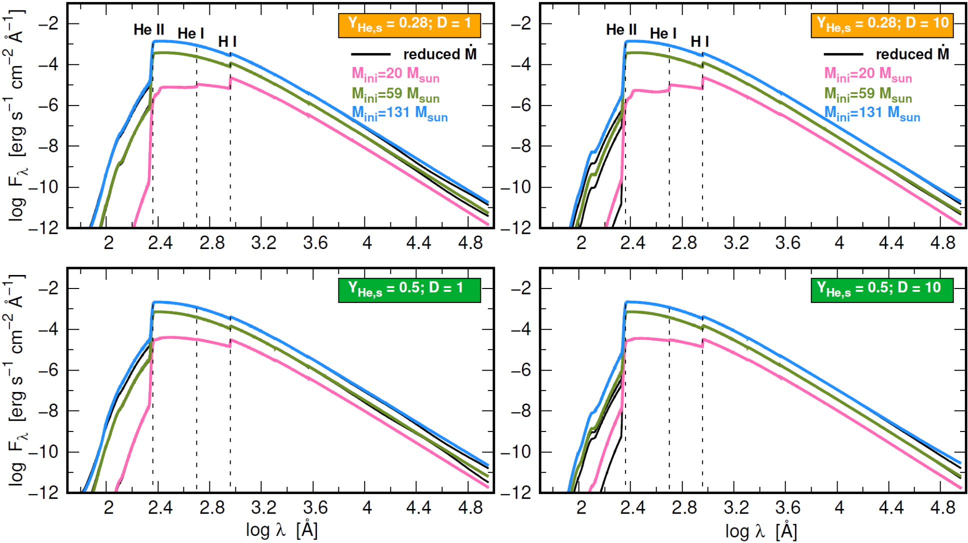
Credit: NASA

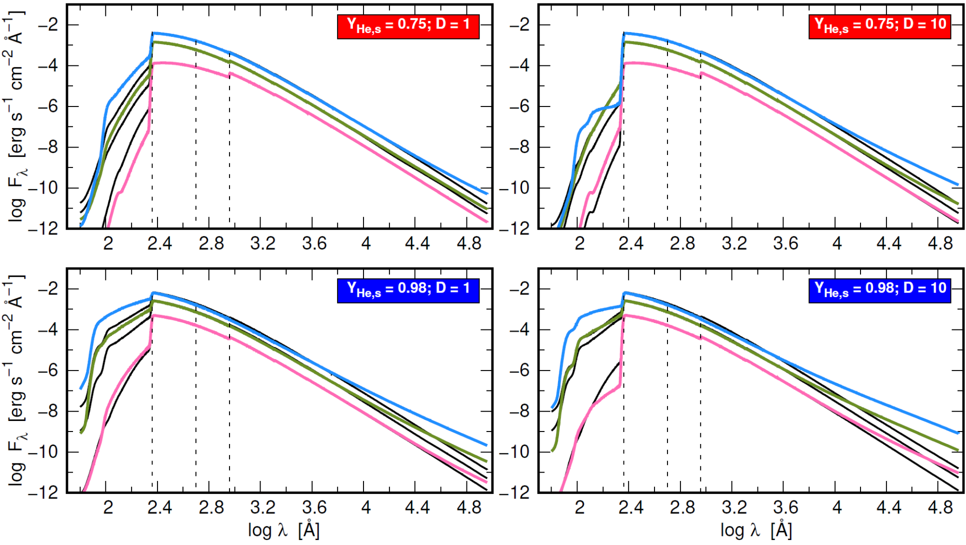
Parameters of the models

M_{ini} [$M_\odot$]	log T_{eff} [K]	log L_* [$L_\odot$]	log $\dot{M}$ [$M_\odot$/yr]	Y_S	Y_C	R_* [$R_\odot$]	M_* [$M_\odot$]	v_{rot} [km/s]
20	4.58	4.68	-8.48	0.28	0.34	4.93	20.0	695
20	4.65	4.97	-7.80	0.50	0.55	5.01	20.0	675
20	4.74	5.29	-6.89	0.75	0.78	4.95	19.8	650
20	4.88	5.58	-5.77	0.98	1.00	3.58	19.2	702
20	5.08	5.67	-5.49	0.84	0.10*	1.55	16.8	994
59	4.74	5.75	-7.00	0.28	0.36	8.14	58.9	421
59	4.79	5.94	-6.70	0.50	0.57	8.31	58.7	428
59	4.84	6.13	-5.82	0.75	0.79	8.08	58.3	422
59	4.92	6.29	-4.92	0.98	1.00	6.68	55.3	404
59	5.14	6.34	-4.70	0.68	0.10*	2.60	49.4	755
131	4.76	6.29	-6.17	0.28	0.30	13.71	130.8	905
131	4.79	6.42	-5.89	0.50	0.52	14.26	129.9	925
131	4.84	6.57	-4.96	0.75	0.76	13.63	126.8	820
131	4.93	6.69	-4.27	0.98	0.99	10.18	112.5	520
131	5.14	6.68	-4.23	0.56	0.10*	3.82	93.3	587

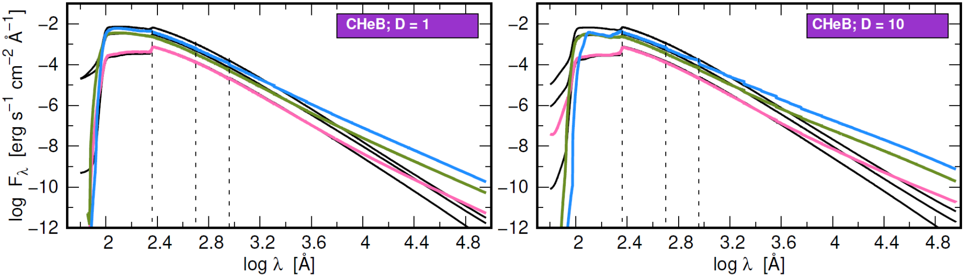
Spectral energy distributions



Spectral energy distributions



Spectral energy distributions



Spectral energy distributions

- The maximum emission in far-UV and extreme-UV regions
- With increasing $M_{\rm ini}$, the luminosity and the resulting flux also increase
- The amount of emitted UV ionizing radiation increases during the evolution of the stars
- CHB phases
  - Decreasing $\dot{M}$ and clumping has no significant influence on emitted radiation (only small differences at wavelengths $\lambda < 227$ Å and $\lambda > 10000$ Å)
- These differences are higher and more visible in the CHeB phases

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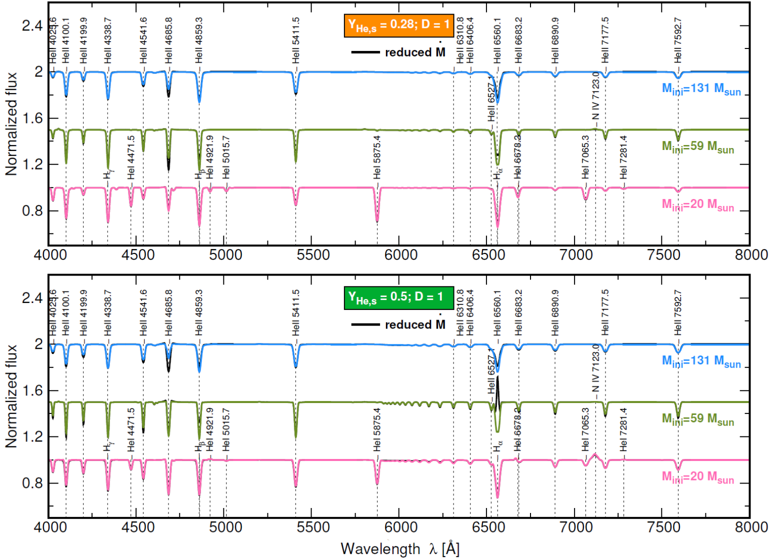
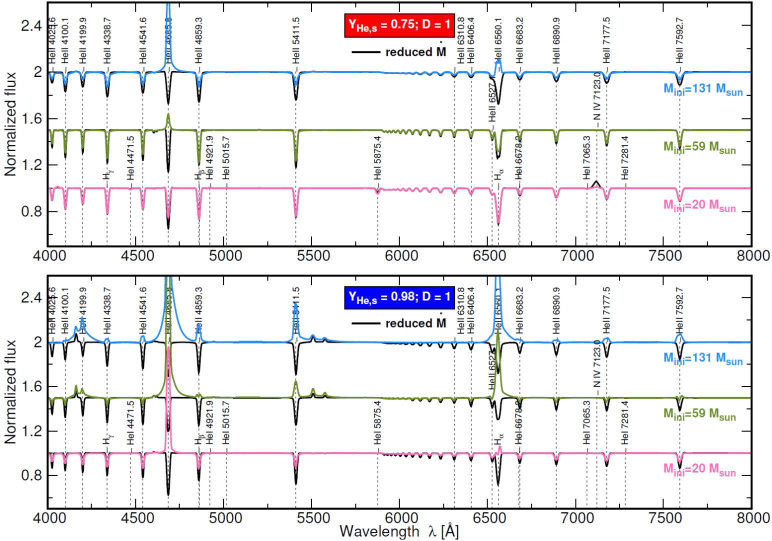
Credit: NASA

Effect of mass loss



Effect of mass loss



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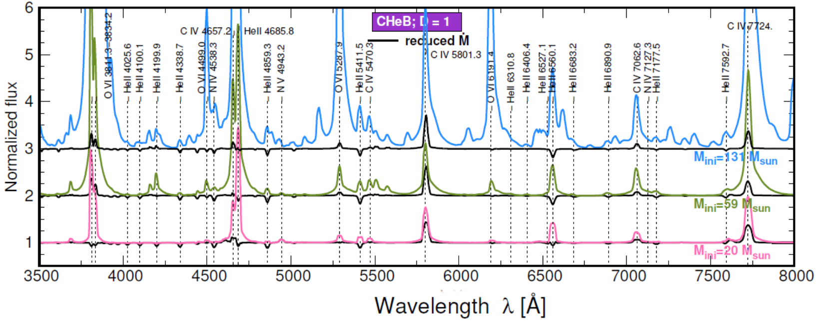

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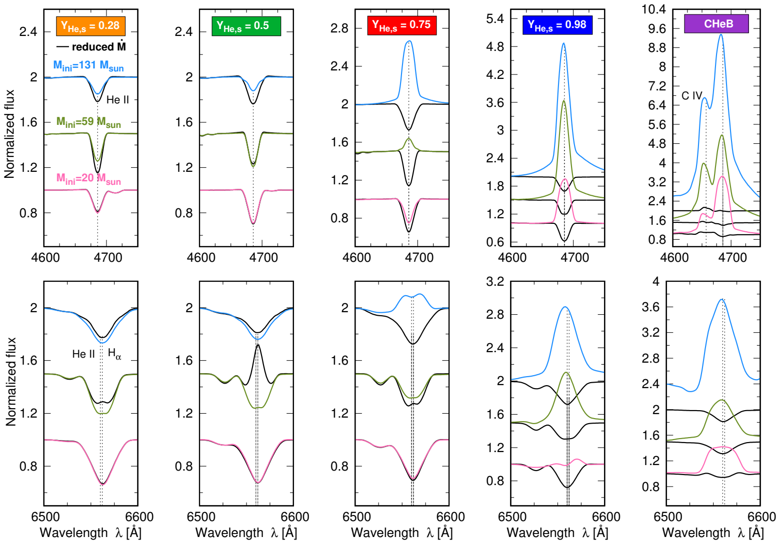
Effect of mass loss



Effect of mass loss

- Early evolutionary phases
  - WEAK AND OPTICALLY THIN WINDS, i.e., TWUIN stars
  - Assumed mass loss has no significant effect
- Later evolutionary phases
  - STRONG AND OPTICALLY THICK WINDS, i.e., WR stars
  - Assumed mass loss has a strong effect
- Almost no any metal lines but strong He II emission lines
- Similar effect is seen in the UV and IR regions (see Kubátová et al., 2019)
- All this is a consequence of the adopted $\dot{M}$ prescriptions in the calculations

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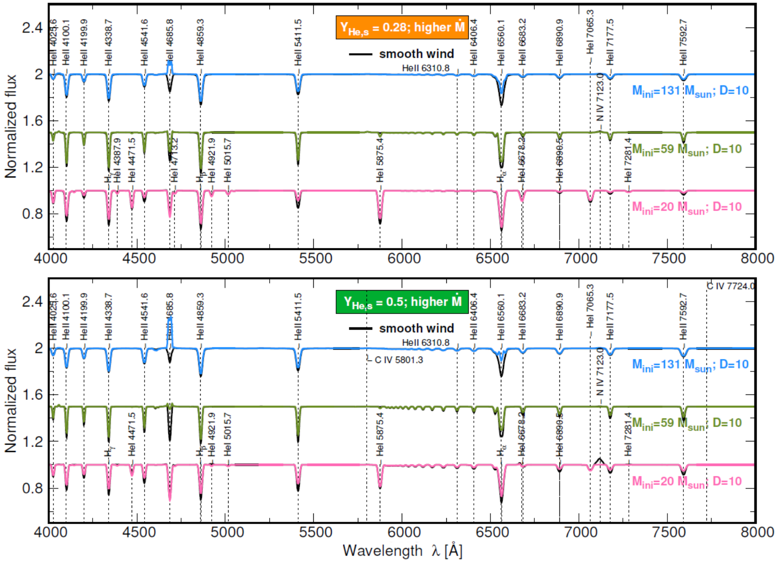
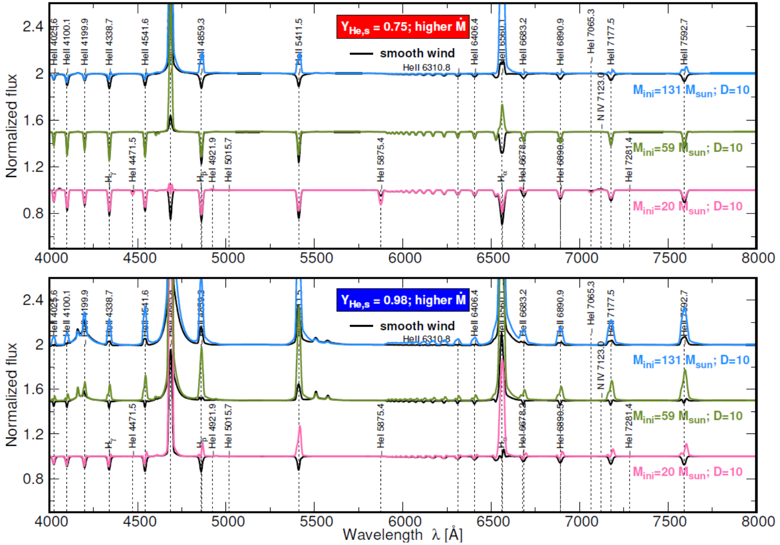
Credit: NASA

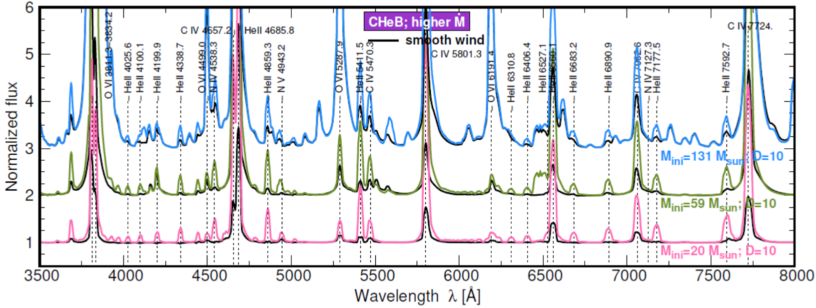
Effect of clumping



Effect of clumping



Effect of clumping



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Credit: NASA

Effect of clumping

- CHB phases
  - higher $\dot{M}$ - clumping reduces absorption lines or makes emission lines stronger
  - reduced $\dot{M}$ - spectra stay almost unchanged with increasing clumping
- The importance of clumping is more pronounced in the CHeB phases
  - higher $\dot{M}$ - very strong effect of clumping
  - reduce $\dot{M}$ - no significant effect of clumping
- Similar effect is seen in the UV and IR regions (see Kubátová et al., 2019)

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Credit: NASA

Spectral classification

Morgan–Keenan spectroscopic classification scheme

$M_{\rm ini}$	$Y_{\rm S}$	$D = 1$		$D = 10$	
		reduced $\dot{M}$	higher $\dot{M}$	reduced $\dot{M}$	higher $\dot{M}$
20	0.28	O 8.5 V	O 8.5 V	O 9.5 V	O 9 V
20	0.5	O 5.5 III	O 6 III	O 7 III	O 7 III
20	0.75	<O 4 III	<O 4 III	<O 4 III	O 5 I
20	0.98	O 4 III	<O 4 I	<O 4 III	O 4 I
20	pMS	WO 2 (–)	WO 1	WO 2 (–)	WO 1 (WO 3)
59	0.28	<O 4 III	<O 4 III	<O 4 III	<O 4 III
59	0.5	<O 4 III	<O 4 III	<O 4 III	<O 4 I
59	0.75	O 4 III	<O 4 I	<O 4 III	<O 4 I
59	0.98	<O 4 III	<O 4 I	<O 4 III	(WO 2 or WO 1)
59	pMS	WO 1 (WO 3)	WO 1	WO 1 (WO 3)	WO 1
131	0.28	O 4 III	<O 4 III	<O 4 III	<O 4 I
131	0.5	O 4 III	<O 4 III	<O 4 III	<O 4 I
131	0.75	<O 4 III	<O 4 I	O 4 III	<O 4 I
131	0.98	<O 4 III	O 4 I	<O 4 III	WO 4 (WO 2 or WO 1)
131	pMS	WO 1 (WO 3)	WO 1	WO 1 (WO 3)	WO 1

Spectral classification

Morgan–Keenan spectroscopic classification scheme

M_{ini}	Y_S	D			
20					
20					
20					
20					
20					
59					
59					
59					
59					
59					
131					
131					
131					
131					
131	pMS	WO 1 (WO 3)	WO 1	WO 1 (WO 3)	WO 1

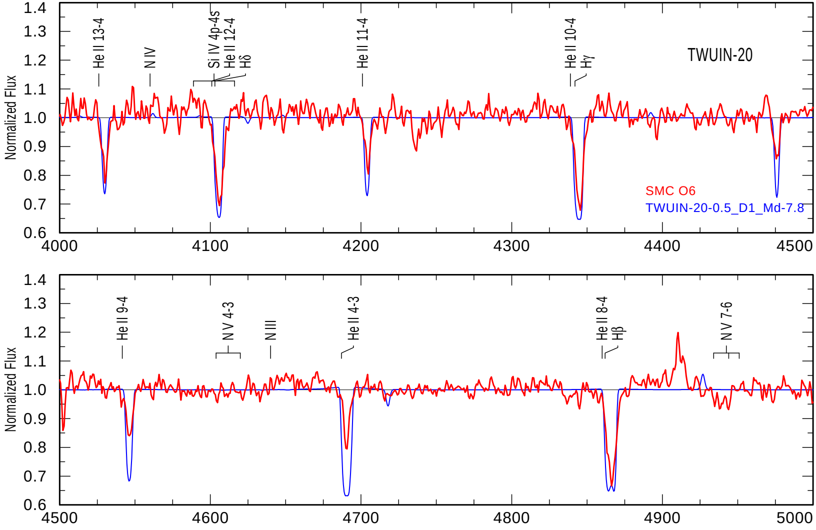
Message for potential observers

- At low-metallicity ($\sim 0.02\,Z_\odot$) we predict:
  - Very hot early O-type stars (i.e., $< O\,4$) during the CHB phases (i.e., TWUIN stars)
  - WO-type stars in the CHeB phases
- The detection of a very hot star without almost any metal lines but with strong He II emission lines that is consistent with some very early-O type giant or supergiant would be a strong candidate for a star resulting from chemically-homogeneous evolution

Kubátová et al., A&A 623, A8 (2019)

Comparison to observations from Sextants A

Comparison to O6 star (Garcia et al., MNRAS 484, 422)



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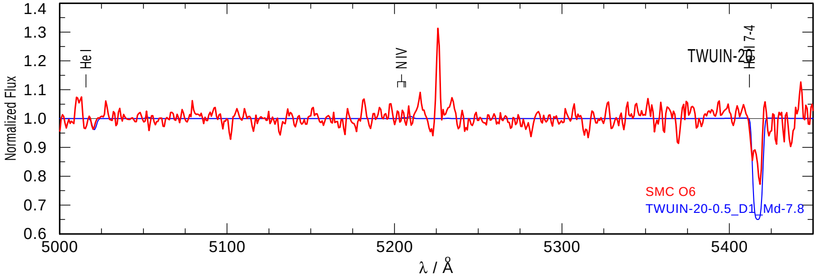
Comparison to O6 star (Garcia et al., MNRAS 484, 422)



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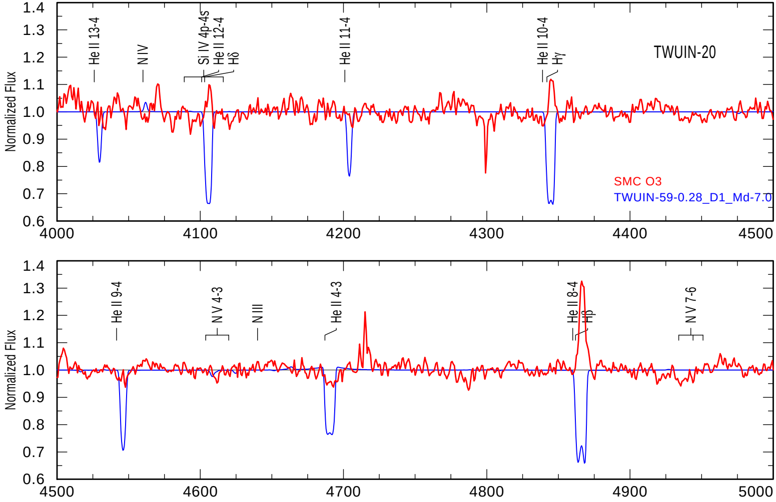
Credit: NASA

Comparison to observations from Sextants A

Comparison to O3 star (Garcia et al., MNRAS 484, 422)



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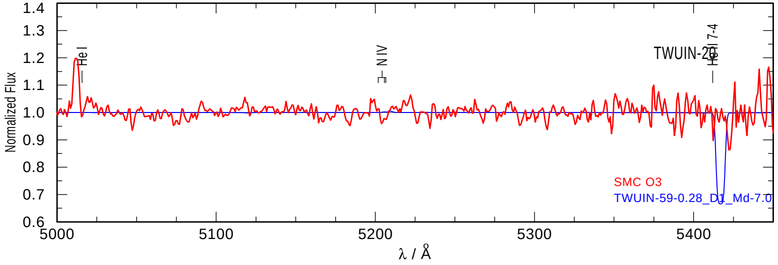

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Credit: NASA

THANK YOU FOR YOUR ATTENTION!