Wolf-Rayet Stars
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Do rapidly-rotating massive stars at low metallicity form Wolf–Rayet stars?

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The evolution of massive stars is strongly influenced by their initial chemical composition. We have computed rapidly-rotating massive star models with low metallicity ($\sim$1/50 $Z_\odot$) that evolve chemically homogeneously and have optically-thin winds during the main sequence evolution. These luminous and hot stars are predicted to emit intense mid- and far-UV radiation, but without the broad emission lines that characterize WR stars with optically-thick winds. We show that such Transparent Wind UV-Intense (TWUIN) stars may be responsible for the high number of He II ionizing photons observed in metal-poor dwarf galaxies, such as I Zw 18. We find that these TWUIN stars are possible long-duration gamma-ray burst progenitors.

1 Stellar evolution at low Z

Massive stars at very low metallicity (1/50 $Z_\odot$) evolve differently to those at solar Z (Meynet & Maeder 2002; Brott et al. 2011; Yoon et al. 2012; Yusof et al. 2013). We have computed low-Z stellar evolutionary models in the mass range 9–300 $M_\odot$ and with initial rotational velocities between 0–600 km/s (Szécsi et al. 2015). Fig. 1 shows a representative sample of the computed tracks in the Hertzsprung-Russell (HR) diagram. The slow rotators ($<$ 200 km/s) follow the normal evolutionary path which proceeds redwards from the zero-age main-sequence (ZAMS). After core-hydrogen burning, these stars develop a distinct core-envelope structure (i.e. no enhanced mixing between the core and the surface), burn helium on the red-supergiant branch and would explode as Type IIp supernovae (Langer 2012; Yoon et al. 2012; Szécsi et al. 2015).

On the other hand, the fast rotators ($>$ 300 km/s) evolve bluewards from the ZAMS, and undergo chemically-homogeneous evolution. In this case, the mixing timescale is significantly shorter than the main-sequence lifetime of these stars, so all the nuclear burning products are mixed throughout the star. These stars stay compact and hot, spending their post-main-sequence lifetimes as fast rotating helium stars and would, according to the collapsar scenario, explode as long-duration gamma-ray bursts (lGRBs) (Yoon & Langer 2005; Woosley & Heger 2006; Yoon et al. 2006; Brott et al. 2011; Szécsi et al. 2015).

In this work, we aim to understand the observational properties of the potential lGRB progenitor stars during their main sequence lifetimes.

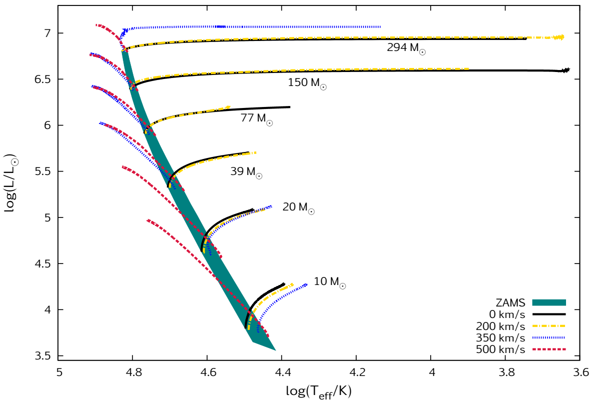

Fig. 1: Evolutionary tracks in the HR diagram during the core-hydrogen-burning phase for models with initial masses between 10–294 $M_\odot$ (see labels) and initial rotational velocities of 0, 200, 350 and 500 km s^{-1}, with a composition of 1/50 $Z_\odot$ (Szécsi et al. 2015). The green shading identifies the zero-age main-sequence.

2 Transparent Wind UV-Intense (TWUIN) stars

2.1 TWUIN stars are not WR stars

Chemically-homogeneously-evolving stars were so far understood to be WR stars during their main-sequence evolution based on their position in the HR diagram (on the hot side of the ZAMS) and their surface composition (enhanced helium abundance). However, WR stars have optically thick winds which lead to the spectral emission lines observed, so in order to decide if chemically-homogeneously-evolving stars are WR stars or not, one needs to analyse their wind properties.

We have estimated the optical depth of the wind (τ) in the chemically-homogeneously-evolving stars in our simulations[1] following Langer (1989). Fig. 2 shows the HR diagram of these stellar models with the wind optical depth colour coded. During most of their main-sequence lifetimes, these stellar models have *optically-thin winds* (i.e. $\tau \lesssim 1$). Therefore, they are not expected to show the broad emission lines in their spectra that characterize WR-type stars. On the other hand, they have luminosities up to 10^7 $L_\odot$ and surface temperatures up to 80 kK. Therefore, they emit intense UV radiation and photoionize their surroundings. To highlight that these hot stars with weak winds would look different from classical WR stars, we call them Transparent Wind Ultraviolet Intense (TWUIN) stars.

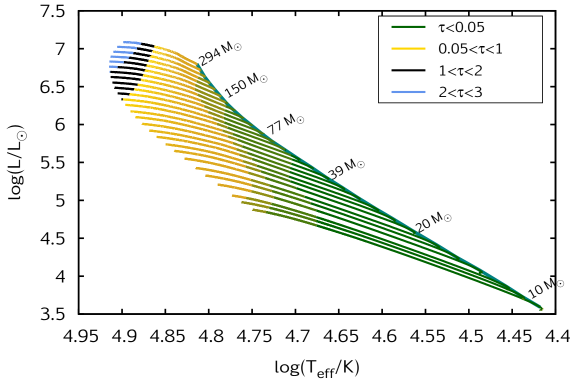

Fig. 2: HR diagram of low-Z stellar models with $v_{\rm ini}$=500 km s^{-1} (chemically-homogeneous evolution) and masses between 9–294 $M_\odot$. Only the core-hydrogen burning phase is plotted (cf. Fig. 4). The colouring marks the wind optical depth τ according to Langer (1989). See Szécsi et al. (2015) for more details.

TWUIN stars are rapidly-rotating, main-sequence stars which are undergoing chemically-homogeneous evolution and have $\tau \lesssim 1$, predicted by our stellar simulations with low-Z (1/50 $Z_\odot$ ~ 1/10 $Z_{\rm SMC}$). Based on the empirical distribution of rotational velocities for O stars in the Small Magellanic Cloud (SMC) by Mokiem et al. (2006), we expect that at least 10%, but possibly more, of the massive stars in a given starburst would be influenced by chemically-homogeneous evolution in a 1/50 $Z_\odot$ environment.

2.2 Ionizing photons in I Zw 18

I Zw 18 is a blue compact dwarf galaxy (Legrand et al. 1997; Aloisi et al. 1999; Izotov et al. 1999; Schaerer et al. 1999; Shirazi & Brinchmann 2012; Kehrig et al. 2013) with very low metal content (12+log(O/H)=7.17 → $Z_{\rm IZw18} \simeq 1/50$ $Z_\odot$, Lebouteiller et al. 2013). Kehrig et al. (2015) observed I Zw 18 and found an unusually high He II photon flux of Q(He II)$^{\rm obs} \approx 10^{50}$ s^{-1}, which could not be attributed to the rather small WR stellar population in this galaxy (Crowther & Hadfield 2006). Kehrig et al. (2015) therefore proposed that Pop III stars could be responsible for the corresponding ionizing radiation (see also Heap et al. 2015). However, while the gas in I Zw 18 is very metal poor, it is not primordial, so the presence of Pop III stars in I Zw 18 is debatable.

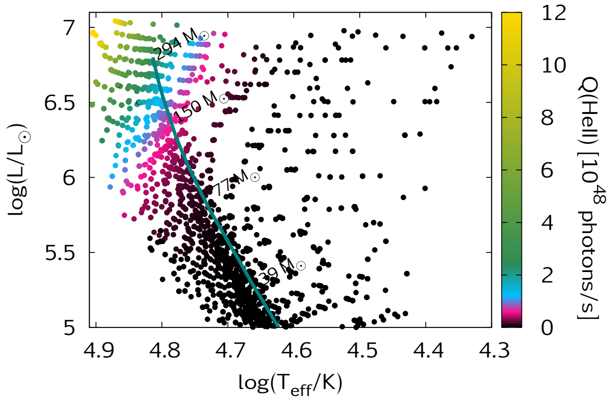

Fig. 3: Dots of equal timesteps (10^5 yr) of our low-Z stellar models (both, slow and fast rotators) in the HR diagram. The thick green line marks the ZAMS. The colouring represents the photon number rate in the He II continuum produced by our models, based on the black body approximation (cf. Szécsi et al. 2015). TWUIN stars are left from the ZAMS; the most massive of them emit as much as 10^{49} He II ionizing photons per second.

In our simulations, the fast rotators evolve chemically homogeneously and become TWUIN stars during their main-sequence lifetime. According to Fig. 3, the hottest and most luminous of the TWUIN stars (~300 $M_\odot$) produce a He II ionizing flux in the order of 10^{49} photons s^{-1}. This means that the total He II flux, Q(He II)$^{\rm obs}$ observed in I Zw 18 could be produced by just a few very massive TWUIN stars.

It may be more likely that the observed ionizing flux is produced by TWUIN stars of ~100 $M_\odot$, which emit a He II ionizing flux of about 5×10^{48} pho-

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[1] We use the prescription of Hamann et al. (1995) for the winds of our models with reduction by a factor of 10 as suggested by Yoon et al. (2006), as this reduction gives a mass-loss rate comparable to the most commonly adopted one by Nugis & Lamers (2000) (see Fig. 1. of Yoon 2015). The Hamann et al. (1995) prescription is applied together with a metallicity dependence of $\dot{M} \sim Z^{0.86}$ (Vink et al. 2001).

tons s^{-1}. Consequently, about 20 TWUIN stars with 100 $M_\odot$ could explain the observations. Given that the star formation rate for I Zw 18 is about 0.1 $M_\odot$ yr^{-1} (Lebouteiller et al. 2013), this number of TWUIN star appears quite plausible (Szécsi et al. 2015).

2.3 The post-MS phase

TWUIN stars are expected to spend their post-main-sequence evolution as WR stars with optically-thick winds, see Fig. 4. This finding is in accordance with our interpretation of the observations of I Zw 18: while during core hydrogen burning these models are in the TWUIN star phase, but during their post-main-sequence lifetime they would constitute the small WR population found in the galaxy.

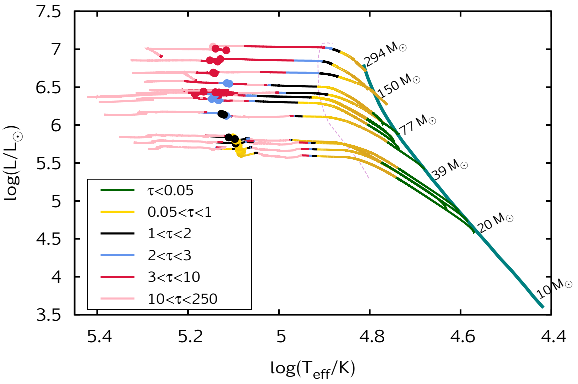

Fig. 4: HR diagram depicting the post-main-sequence phase of the TWUIN stars (v_{ini}=500 km/s). The thick green line marks the ZAMS, the thin dashed line marks the end of core hydrogen burning. The colouring indicates the wind optical depth τ according to Langer (1989). Dots mark approximately where the stars burn helium in the core.

3 Conclusions

We have presented stellar evolutionary predictions for massive stars at the composition of the dwarf galaxy I Zw 18. We found that the main-sequence stars populate both sides of the ZAMS. Our fast rotating stars, which may comprise more than 10% of all massive stars, evolve chemically homogeneously and bluewards in the HR diagram. We call them TWUIN stars and note that they are not WR stars in the classical sense. Due to their extremely high effective temperatures and the optically-thin winds, TWUIN stars would have very high ionizing fluxes. We argue that the measured He II flux of I Zw 18 as well as weakness of Wolf-Rayet features is compatible with a population of TWUIN stars in this galaxy.

The TWUIN stars, which have weak winds because of their low metal content, are possible lGRB progenitors, as they do not lose enough angular momentum in the wind. Our conclusion is that the high HeII flux observed in dwarf galaxies can be a signpost for upcoming lGRBs in these objects. Additionally, the observed high HeII flux may argue that chemically-homogeneous evolution, which leads to the TWUIN stars, is indeed happening in nature.

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Jose Groh: 1) Are you assuming a Langer et al. (1989) relationship for estimating the wind optical depth (i.e. β=2, v_{inf}=2000 km/s)?

2) Also, have you estimated the LGRB rate if they all indeed come from chemically-homogeneous stars?

Dorottya Szécsi: 1) Yes.

2) Yes, and we found that our results are consistent with the study of Yoon et al. (2006), who found a very similar threshold rotational velocity for chemically-homogeneous evolution for stars below 60 $M_\odot$ as the present work. While we shall present the post-main-sequence evolution of our models in a forthcoming study, from our models we can expect a similar ratio of long-duration GRBs to supernovae of the order of 1–3% as Yoon et al. (2006).

Paul Crowther: A couple of dozen fast rotator very massive stars (100 $M_\odot$+) are required to reproduce $Q_2(He^2+) \sim 10^{50}$ in I Zw 18. But this requires that *all* VMSs are fast rotators given its 30 Doradus-like (i.e. 0.1 $M_\odot^{out}$ yr^{-1}) star formation rate (Izotov et al. 1999), doesn't it?

Dorottya Szécsi: We have calculated that, assuming a star formation rate of 0.1 $M_\odot$/yr, about 10–20% of the massive stars need to be fast rotators (i.e. chemically-homogeneously evolving stars) in order to explain the observed He II flux. Indeed, based on the empirical distribution of rotational velocities for O stars in the SMC by Mokiem et al. (2006), up to 20% of the very massive stars could undergo chemically-homogeneous evolution.

Carolina Kehrig: Which are the highest values of He II/H(β) (i.e. Q(He II)/Q(H)) predicted by your most-massive hottest models?

Dorottya Szécsi: Our hottest TWUIN star model with $M_{ini} = 294\,M_\odot$ predicts a value of $\log[Q(\mathrm{He\,II})/Q(\mathrm{H})] = -1.75$.