Stromlo Stellar Tracks: the importance of non-Solar scaled abundances for massive stars

Kathryn Grasha

Research School of Astronomy and Astrophysics, Australian National University, Canberra ACT, Australia

ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia

I present the Stromlo Stellar Tracks [1], a set of stellar evolutionary tracks for massive stars (>10 $M_\odot$), computed by modifying the `Modules for Experiments in Stellar Astrophysics` (MESA) 1D stellar evolution package, to fit the Galactic Concordance abundances for massive Main-Sequence stars. Until now, all stellar evolution tracks are computed at solar, scaled-solar, or alpha-element enhanced abundances, and none of these models correctly represent the observed abundances of H II regions in the Milky Way or Magellanic Clouds at a given metallicity [2, 3]. This paper is the first implementation of Galactic Concordance abundances to stellar evolution models. I find that adopting Galactic Concordance abundances can significantly affect the evolution of main-sequence, massive hot stars in order to estimate accurate stellar outputs (L, $T_{\rm eff}$, g), which, in turn, have a significant impact on determining the ionising photon luminosity budgets. I additionally support prior findings of the importance that rotation plays on the evolution of massive stars and their ionizing budget. The evolutionary tracks for our Galactic Concordance abundance scaling provides a more physically motivated approach than simple uniform abundance scaling with metallicity for the analysis of H II regions and have considerable implications on predictions for nebular emission lines and line diagnostics. Moving beyond assumptions of the Solar elemental abundance scaling methods is critically needed to accurately interpret emission lines from theoretical models, the primary source of our physical understanding of the formation and evolution of galaxies. These tracks will allow consistent abundance ratios to be used in stellar population synthesis and photoionisation models to derive accurate galaxy diagnostics for the first time.

Background

A simple stellar population model describes how a coeval stellar population at a given mass, metallicity, and elemental abundance pattern evolves over its lifetime, referred to as "stellar evolution tracks". Stellar tracks are computed from stellar evolution theory and large observational stellar libraries. Stellar tracks require a set of elemental abundance ratios as an input parameter and have previously been calculated by scaling the relative abundance ratios to Solar. However, it is now known that Solar relative abundance ratios do not match Galactic Concordance abundances. Because of this, stellar tracks and opacity tables that represent the observed abundance ratios in the Milky Way and nearby galaxies need to be computed within current stellar evolution models to allow for self-consistency in stellar population synthesis and photoionisation models.

Stellar Evolution Calculations

The Stromlo Stellar Tracks [1] present stellar evolution models with the scaling abundances based on 'Galactic Concordance' abundances [3]. I use the MESA [4] stellar evolution code within the framework developed by MESA Isochrones and Stellar Tracks [MIST; 5]. The Stromlo Tracks cover the evolution of massive ($10 \leq M/M_\odot \leq 300$) stars with varying rotations ($v/v_{\rm crit}$ = 0.0, 0.2, 0.4) and a finely sampled grid of metallicities ($-2.0 \leq$ [Z/H] $\leq +0.5$; Δ[Z/H] = 0.1).

I focus on massive (>10 $M_\odot$) stars as they have traditionally been neglected in prior stellar evolution models. In addition, massive, rotating stars dominate the ionising budget powering H II regions and are a vital component in controlling the physics that regulates the efficiency of star formation. Using Flexible Stellar Population Synthesis (FSPS; [6]), I generate synthetic spectra for the Stromlo tracks (Figure 1).

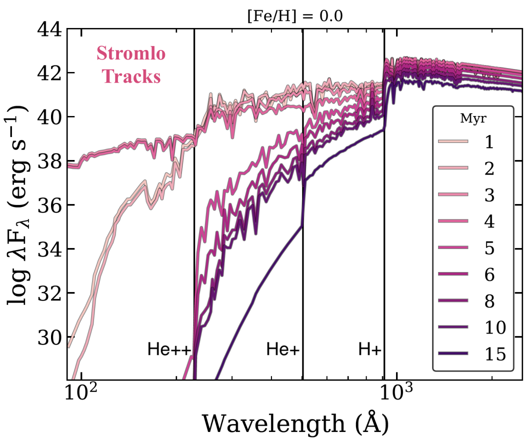

Figure 1: Synthetic spectra calculated using the Stromlo stellar tracks shown at different ages. The vertical lines represent the energies to ionise hydrogen and helium (singly and doubly).

Results – Stellar Rotation and Surface Abundances

Rotation in the massive (>100 $M_\odot$) stars heavily impacts their surface composition (Figure 2). These stars spend the vast majority of their main sequence lifes with enhanced He surface abundances consistent with the Wolf-Rayet evolutionary phase. For non-rotating massive stars, there are no diffusion mechanisms for the transport of chemical elements from the inner convective core to the outer convective shell, and therefore, there is little to no surface enhancement. The impact of rotation in altering the observed surface abundances of stars increases dramatically at lower metallicities.

Results – Stellar Ionising Spectra

Using the synthetic spectra (Figure 1), I calculate the total ionising photon rate Q to constrain the difference

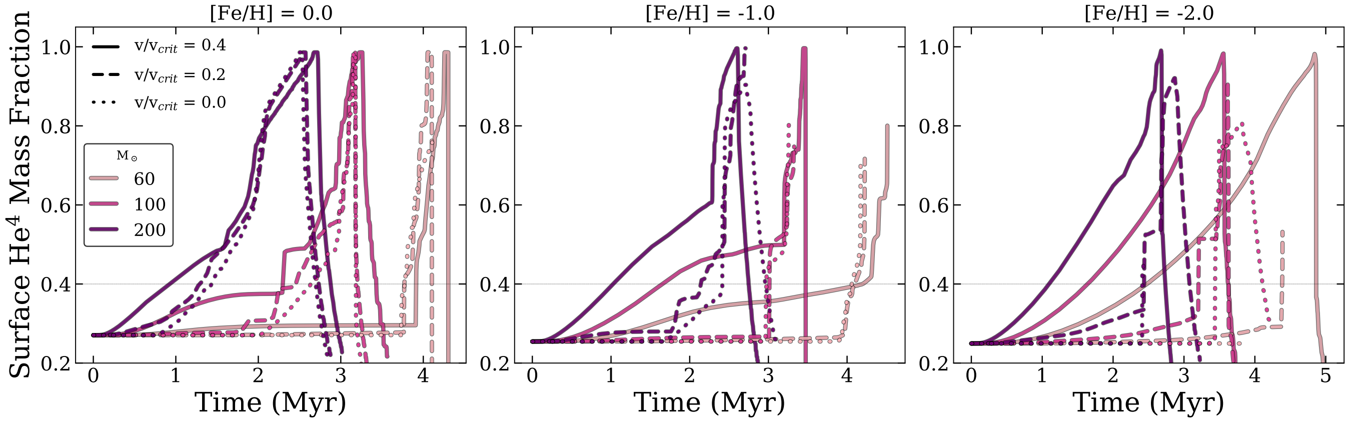

Figure 2: Time evolution of the surface ^{4}He abundances for 60, 100, and 200 $M_{\odot}$ Stromlo stars with $v/v_{\rm crit}$ = [0.4, 0.2, 0.0] (solid, dashed, and dotted lines, respectively) at metallicities of [Fe/H] = [0.0, –1.0, –2.0] (left, middle, and right, respectively). The gray line at 0.4 marks the He abundance that delineates the start of the Wolf-Rayet phase of stellar evolution. The effects of rotation are more important (larger differences) at lower metallicity.

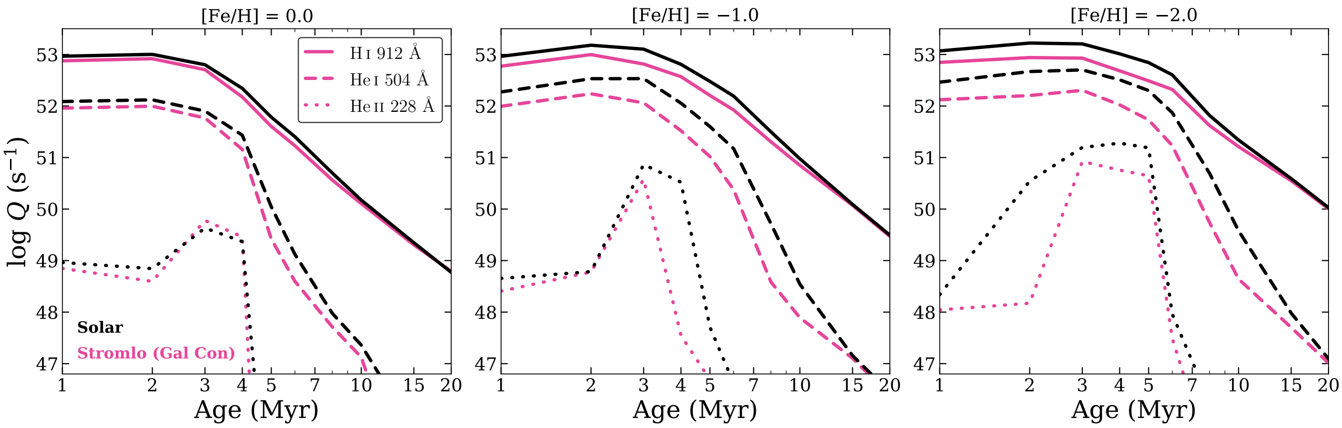

Figure 3: Time evolution of the ionising photon rate Q for the Stromlo models (Gal Con; pink) and Solar abundance models (black) for a 10^{6} $M_{\odot}$ stellar population at [Fe/H] = 0.0 (left), –1.0 (middle), and –2.0 (right). The line-style represent the ionising photons capable of ionising hydrogen H^{+} (912 Å; solid lines), singly ionising helium He^{+} (504 Å; long dashed lines), and doubly ionising helium He^{++} (228 Å; short dotted lines). The ionising photon output for solar-scaled stars is overestimated at all metallicities, with the difference between the ionising budget of Solar and non-Solar becoming substantially larger at lower metallicities.

between Solar versus non-Solar scaled elemental abundances at varying metallicities (Figure 3). Solar-scaled abundances overpredict the stellar ionising spectra with discrepancies of up to 1 dex for the youngest stars at low metallicities. This has an enormous and substantial impact on the observed emission lines and subsequent galaxy diagnostics (SFR, metallicities, etc).

Implications and Future Work

This work demonstrates that it is essential to have a self-consistent picture of how stars ionise their local star-forming sites at different metallicities and abundances. In the future, the Stromlo tracks will be combined self-consistently with nebular photoionisation models, setting the foundation for realistic nebular emission line predictions from the *James Webb Space Telescope*. *JWST* will obtain spectra for 100,000s of galaxies across 13 billion years of cosmic time. These new diagnostics from self-consistent modelling of galactic spectra will enable us to reliably interpret the wealth of data from the next generation of observatories. This undoubtedly will bring about a major advance in our understanding of how the physical properties of galaxies and their elemental compositions have evolved over the history of the universe.

References

[1] Grasha, K., et al. 2021, ApJ, 908, 241
[2] Nieva, M.F., & Przybilla, N. 2012, A&A, 539, A143
[3] Nicholls, D.C., et al. 2017, MNRAS, 466, 4403
[4] Paxton, B., et al. 2011, ApJS, 192, 3
[5] Choi, J., et al. 2016, ApJ, 832, 102
[6] Conroy, C., et al. 2009, ApJ, 699, 486

Short CV

2018: PhD in Astronomy, University of Massachusetts, United States
2018: Laureate Postdoctoral Fellow, Australian National University, Australia
2021: ASTRO 3D Fellow, Australian National University, Australia
2022: DECRA Fellow, Australian National University, Australia