New Stellar Models – Boon or Bane?

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Abstract The impact of new stellar evolution models with rotation on the predictions of population synthesis models is discussed. Massive rotating stars have larger convective cores than their non-rotating counterparts, and their outer layers are chemically enriched due to increased mixing. Together, these two effects lead to hotter and more luminous stars, in particular during later evolutionary phases. As a result, stellar populations containing massive stars are predicted to become more luminous for a given mass and to emit more ionizing photons. Depending on the assumed rotation velocity, rotation causes profound changes in the properties of young stellar populations. These changes are most noticeable at later evolutionary phases and at shorter wavelengths of the spectral energy distribution. Most strikingly, the Lyman continuum luminosity increases by up to a factor of five in O- and Wolf-Rayet stars. Care is required when comparing these models to observations, and some fine-tuning of the models is still required before recalibrations of star-formation indicators should be attempted.

1 Introduction

Population synthesis models aim to predict photometric, spectroscopic, and chemical properties of stellar systems, such as massive star clusters or entire galaxies. Stellar evolution models are at the heart of population synthesis, as these models provide the prescription for the relation between stellar luminosity and mass and their evolution with time. Due to the time scales involved, stellar evolution mostly eludes direct observation and is therefore heavily model-dependent. Nevertheless, great strides have been made over the past decades in the field of massive-star evolution (e.g., [4]; [21]; [16]). Each new generation of evolution models has led to transformational changes in the field of population synthesis. The present epoch marks another such transformation: stellar rotation, which had previously been recognized to be significant for the evolution of massive stars, has finally been implemented self-consistently in evolutionary tracks. In this contribution I will introduce a new set of evolutionary tracks for massive stars that accounts for rotation and discuss how these tracks affect population synthesis models.

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2 Why Do We Need Revised Stellar Evolution Models?

A major breakthrough in our understanding of massive-star properties came with the recognition of stellar mass loss as a main agent in driving evolution ([5]). Powerful stellar winds and outbursts remove stellar mass so that a massive O star on the main-sequence turns into a low-mass Wolf-Rayet (W-R) star towards the end of its life. Mass loss is a key ingredient in all modern evolution models such as those by the Geneva ([28]; [25]; [27]; [3]; [22]) and Padova ([1]; [9]; [10]; [12]) groups. The former model set is implemented in the evolutionary synthesis code Starburst99 ([19]; [30]; [17]).

The mass-loss rates originally derived have now been found to be an overestimate. Inhomogeneities in the winds require the introduction of filling factors which lead to downward corrections of factors of $\sim 5$ ([23]). As a result, stationary stellar winds are insufficient to account for the required decrease of stellar mass from the early to the late evolution of massive stars. However, massive post-main-sequence stars undergo occasional outbursts as Luminous Blue Variables. The total mass lost during this phase is rather uncertain and may very well be comparable to the total mass loss via stellar winds ([29]). If so, the overall validity of the earlier stellar-wind dominated evolution models would still be intact.

While the revised importance of different mass-loss phases may not pose a fundamental problem for previous evolution models, observations of a significant nitrogen enhancement in OB-star atmospheres ([13]) are in fact a challenge. Nitrogen is a by-product of the CN cycle in the stellar nucleus, and an effective mechanism is required to explain its presence on the stellar surface of main-sequence stars. The new, reduced mass-loss rates are too low for the star to shed sufficient mass to expose the processed material prior to the Luminous Blue Variable phase. Alternatively, interior mixing can transport the products of nuclear processing to the surface. This mixing is facilitated by stellar rotation. Support for rotationally induced mixing comes from the observed significant rotation velocities of OB stars ([6]) and their (loose) correlation with the measured nitrogen enhancement ([13]). This provides the motivation for including rotation in stellar evolution models.

3 What is Different in the New Models?

The effects of rotation on the evolution in the Hertzsprung-Russell (HR) diagram depend on the initial stellar mass. Low-mass stars with masses less than $\sim 2 \, M_\odot$ have essentially zero rotation velocity due to magnetic breaking before they reach the main-sequence. Stars in the mass regime between 2 and $\sim 15 \, M_\odot$ have lower effective temperature ($T_{\text{eff}}$) at higher rotation velocity. This simply results from the centrifugal forces which increase the equatorial radius at fixed luminosity ($L$). Fig. 1, which has been taken from [2], illus-
trates this effect. The rotating evolutionary models in this figure assume an initial rotation velocity of 550 km s\(^{-1}\), which subsequently decreases due to angular momentum loss by winds and the increasing stellar radius. At higher stellar masses (> 15 M\(_\odot\)), rotation modifies the interior structure. The convective core becomes larger, and therefore \(L\) increases. At the same time, the enhanced mixing leads to a higher helium surface abundance, and \(T_{\text{eff}}\) increases (see Fig. 1).

![Fig. 1](image_url)  
**Fig. 1** Evolutionary tracks at solar chemical composition with initial rotation velocities of 0 (light solid) and 550 km s\(^{-1}\) (dark solid). The tracks are labeled with the initial stellar masses. From [2].

In order to study the impact of stellar rotation on the properties of stellar populations, the new sets of stellar evolution models with and without rotation of [7] and [11] have been implemented in Starburst99. The two model sets are for chemical compositions of solar and 1/7 solar. The rotation velocities of the rotating models assume an initial value of 40% of the equatorial break-up speed for any initial mass. This value was chosen to approximately reproduce the observed rotation velocities of OB stars. In the following a few representative results of the synthesis calculations are shown. The full suite of simulations can be found in [13]. All models are for single stellar populations following a Kroupa initial mass function (IMF) between 0.1 and 100 M\(_\odot\) ([15]). Three sets of tracks are compared: the original Geneva 1994 mod-
els with high mass loss ([22]) and the new 2012/13 Geneva tracks with and without rotation ([7]; [11]), all for solar and sub-solar chemical composition.

Fig. 2 Comparison of spectral energy distributions at age 4 Myr obtained with three different sets of evolutionary tracks. Solid: previous tracks of [22]; dashed: [7] and [11] without rotation; dash-dotted: [7] and [11] with rotation. Left: solar chemical composition; right: sub-solar.

The resulting spectral energy distributions (SED) at age 4 Myr between 400 Å and 3 μm are shown for solar (left) and sub-solar (right) chemical composition in Fig. 2. As expected from the larger $L$ and $T_{\text{eff}}$ of individual massive stars, the SED of the population exhibits a flux excess when rotation is accounted for. This excess is particularly striking at the shortest wavelengths. On the other hand, the new and old generations of tracks without rotation are rather similar. The difference between the rotating and non-rotating models in the ionizing continuum is more pronounced at solar than at sub-solar metallicity. The reason are the larger numbers of very hot stars at higher metallicity due to the more effective mass-loss by metallicity dependent stellar winds.

Fig. 3 shows the evolution of the number of ionizing photons with time. The models with rotation raise the photon output by up to a factor of $\sim 5$ around 3 to 5 Myr. This quantity is a commonly used measure of the current star formation ([14]), and the derived rates would decrease correspondingly if calibration were based on the rotating models. Similarly, the relation between $L$ and the star-formation rate would be affected, although to a lesser degree. The results in [18] suggest a difference of about 0.2 dex between the rotating and non-rotating models. If $L$ is used as a star-formation tracer, models with rotation would lead to either lower derived rates or a somewhat steeper IMF.

The trend towards hotter, more evolved stars in models with rotation is reflected in the ratio of W-R over O stars (see Fig. 4). Rotation produces more W-R stars relative to O stars between 2.5 and 10 Myr. In particular, additional W-R stars form from less massive ($\sim 25 M_\odot$) stars around 8 to 10 Myr. These stars are the providers of the ionizing photons at this epoch.
in Fig. 3. The W-R/O ratios at solar and sub-solar metallicity are striking different. The new generations of evolution models with and without rotation predict very few W-R stars in metal-poor environments (right part of Fig. 4). This is a consequence of the reduced mass-loss rates compared to the earlier models.

As a final example how different evolution models affect population properties, the CO index is plotted in Fig. 5. The CO index is the equivalent width of the 2.3 μm CO band. It is a proxy for the number of red supergiants. Rotation prolongs the stellar lifetimes because more nuclear fuel is available due to mixing. As a result, the red supergiant phase sets in later. Furthermore, the new models with rotation favor a blueward evolution of metal-rich red supergiants with masses of \( \sim 25 M_\odot \) (cf. the dip at 9 Myr in Fig. 5 [left]). This deficit of red supergiants is mirrored by the excess of W-R stars at that age in Fig. 4.
4 How Do Models and Observations Compare?

The new evolution models with rotation have been carefully calibrated by comparing their predictions for the properties of resolved stellar populations in the Local Group of galaxies. This approach has both advantages and limitations. The Galaxy and its neighbors allow detailed number counts of O stars, blue and red supergiants, and W-R stars. On the other hand, small number statistics are a concern, and properties like the output of Lyman continuum photons are challenging to measure in individual stars. A complementary method of testing stellar evolution models is via unresolved populations in more distant galaxies. This effort is currently underway by our group ([20]).

Since the effects of rotation on population properties become most pronounced in very evolved stellar species, we are focusing on galaxies exhibiting spectral signatures of W-R stars, a.k.a. W-R galaxies ([26]). A complete sample of W-R galaxies was compiled from the SDSS DR7 catalog. This sample of about 300 galaxies covers the distance range 2.2 to 650 Mpc and has oxygen abundances log(O/H)+12 between 7.2 and 8.7. The ratio of broad (non-nebular) He II $\lambda$4686 over H$\beta$ can be used as a proxy of W-R over O-stars, with most of the W-R stars belonging to the nitrogen-rich WN sequence. Similarly, the ratio of C IV $\lambda$5808 over H$\alpha$ indicates the relative number of carbon-rich WC stars. These quantities are plotted in Fig.6, which compares the measured ratios to those predicted by the models. The comparison for He II $\lambda$4686, i.e. for predominantly WN stars, suggests no clear preference for either the rotating or non-rotating models at solar chemical composition, as there is little difference between the models in the observed age range. The data for metal-poor galaxies favor the rotating models, which are a better match for the relatively high observed ratios. The results for C IV $\lambda$5808 clearly favor the models with rotation, which can reproduce the number of WC stars at epochs $> 5$ Myr. However, the models fail at low metallicity.
There are essentially no WC stars in the models, whereas the observed line strengths suggest the presence of a significant WC population.

![Fig. 6](image_url)

**Fig. 6** Comparison of the observed (symbols) and predicted (lines) ratios of He II $\lambda$4686 over H$\beta$ (left) and C IV $\lambda$5808 over H$\alpha$ (right). The measured values are shaded according to metallicity, whose scale is indicated in the lower right of each figure. The dark solid and dashed lines are the non-rotating the rotating models at solar metallicity, respectively. The light lines are the corresponding models at sub-solar metallicity.

5 What Improvements are Needed?

Inclusion of rotation in stellar evolution models leads to substantial revisions of the predicted properties of populations containing massive stars. Realistic evolutionary synthesis models must account for the effects of rotation in massive stars. However, whenever a new generation of transformational evolution models becomes available, additional fine-tuning is still necessary and care is advised when comparing models and observations. The newly released set of evolutionary tracks of [7] and [11] allows the user to gauge the effects of rotation by providing tracks with zero and with high (40% break-up) rotation velocities. These values should bracket the observations. While zero rotation is clearly in conflict with observations of individual stars, the models with high rotation produce population SEDs which appear unexpectedly hot and luminous in the ultraviolet. Careful tests to support or reject this prediction are required.

The models discussed here describe the evolution of *single* stars. Recent surveys clearly establish that at least 50% of all massive stars are not single but binaries and that about 70% of these binaries experience interaction in the course of their evolution [24]. The interaction processes include envelope stripping of the primary, accretion and spin-up in the secondary, or even a full merger of the two components. Interactions in binaries may be as relevant for interior mixing and mass removal as single-star rotation and stellar winds.
Since mass loss via radiatively driven winds decreases with metallicity, one expects the effects of binary evolution to become more noticeable at lower metallicity. The failure of the rotating single-star models to generate large enough numbers of W-R stars at sub-solar chemical composition points in this direction. Realistic evolution models accounting for both single-star and binary evolution (8) may be the next challenge in the future.

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References
1. Bressan, G., Fagotto, F., Bertelli, G., & Chiosi, C. 1993, A&AS, 100, 647
2. Brott, I., de Mink, S. E., Cantiello, M., et al. 2011, A&A, 530, A115
3. Charbonnel, C., Meynet, G., Maeder, A., Schaller, G., & Schaerer, D. 1993, A&AS, 101, 415
4. Chiosi, C., & Maeder, A. 1986, ARA&A, 24, 329
5. Conti, P. S. 1976, Mem. Soc. R. Sci. Liege, 9, 193
6. Dufton, P. L., Langer, N., Dunstall, P. R., et al. 2013, A&A, 550, 109
7. Ekstrom, S., Eggenberger, P., Meynet, G., et al. 2012, A&A, 537, 146
8. Eldridge, J. J. 2012, MNRAS, 422, 794
9. Fagotto, F., Bressan, A., Bertelli, G., & Chiosi, C. 1994a, A&AS, 104, 365
10. Fagotto, F., Bressan, A., Bertelli, G., & Chiosi, C. 1994b, A&AS, 105, 29
11. Georgy, C., Ekstrom, S., Eggenberger, P., et al. 2013, A&A, 558, 103
12. Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
13. Hunter, I., Brott, I., Langer, N., et al. 2009, A&A, 496, 841
14. Kennicutt, R. C., & Evans, N. J. 2012, ARA&A, 50, 531
15. Kroupa, P. 2008, in Pathways Through an Eclectic Universe, ed. J. H. Knapen, T. J. Mahoney, & A. Vazdekis (San Francisco: ASP), 3
16. Langer, N. 2012, ARA&A, 50, 107
17. Leitherer, C., & Chen, J. 2009, New Astronomy, 14, 356
18. Leitherer, C., Ekstrom, S., Meynet, G., et al. 2014, ApJS, in preparation
19. Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
20. Levesque, E. M., Agienko, K., Leitherer, C., et al. 2014, ApJ, in preparation
21. Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143
22. Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&A, 269
23. Puls, J., Vink, J. S., & Najarro, F. 2008, A&ARv, 16, 209
24. Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Sci, 337, 444
25. Schaerer, D., Charbonnel, C., Meynet, G., Maeder, A., & Schaller, G. 1993a, A&AS, 102, 339
26. Schaerer, D., Contini, T., & Pindao, M. 1999, A&AS, 136, 35
27. Schaerer, D., Meynet, G., Maeder, A., & Schaller, G. 1993b, A&AS, 98, 52
28. Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
29. Smith, N. 2009, in Massive Stars: From Pop III and GRBs to the Milky Way, eds. M. Livio & E. Villaver (Cambridge: CUP), 187
30. Vázquez, G. A., & Leitherer, C. 2005, ApJ, 621, 695 Leitherer, C. 2005, ApJ, 621, 695