Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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Revision of Star-Formation Measures

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Abstract. Rotation plays a major role in the evolution of massive stars. A revised grid of stellar evolutionary tracks accounting for rotation has recently been released by the Geneva group and implemented into the Starburst99 evolutionary synthesis code. Massive stars are predicted to be hotter and more luminous than previously thought, and the spectral energy distributions of young populations mirror this trend. The hydrogen ionizing continuum in particular increases by a factor of up to 3 in the presence of rotating massive stars. The effects of rotation generally increase towards shorter wavelengths and with decreasing metallicity. Revised relations between star-formation rates and monochromatic luminosities for the new stellar models are presented.

Keywords. stars: evolution, stars: rotation, galaxies: dwarf, galaxies: evolution, galaxies: irregular, galaxies: starburst, galaxies: stellar content

1. Background

The star-formation rates of galaxies are commonly determined from the integrated light emitted at a certain wavelengths, such as the V band. Comparison with theoretically predicted mass-to-light (M/L) ratios can in principle provide the total stellar mass and, in combination with an appropriate timescale, the star-formation rate. This fundamental methodology goes back to Tinsley's (1980) pioneering work. Although the reasoning is immediately intuitive, two major challenges need to be tackled.

The first challenge is the a priori unknown stellar initial mass function (IMF). Observed values of $M/L_{\rm V}$ in galaxy centers are around $5-100$. At the same time we know that the main contributors to the galaxy light are upper main-sequence (MS) and evolved low-mass stars. These stars have $M/L_{\rm V} \approx 1$. To put these numbers into perspective, the average $M/L_{\rm V}$ of all known stars within 20 pc of the Sun is about $1-2$ (Faber & Gallagher 1979), and an early-type MS star has $M/L_{\rm V} \approx 10^{-2}$. Since the mass-to-light ratio in galaxy centers is not too sensitive to dark matter (at least for disk galaxies; cf. E. Brinks' talk at this conference), the apparent discrepancy suggests that most of the stellar mass is hidden from view because most stars have lower luminosity, and therefore have lower mass than indicated by the spectrum. For the purpose of this paper I will assume we can correct for this effect by assuming a known, universal IMF (Kroupa 2007 and this conference).

The second challenge involves the M/L of individual stars of all masses. At the high-mass end, this quantity is not accessible to direct measurements and can only be predicted by stellar evolution models: masses are poorly known because of the scarcity of very massive binaries with mass determinations, and luminosities are elusive because most of the stellar light is emitted in the ionizing ultraviolet. The purpose of this paper is to discuss how the latest generation of stellar evolution models including rotation differs from its predecessor, and how these new models affect the predictions of the evolutionary synthesis code Starburst99 (Leitherer *et al.* 1999; Vázquez & Leitherer 2005). Some of the results presented here can be found in Vázquez *et al.* (2007).

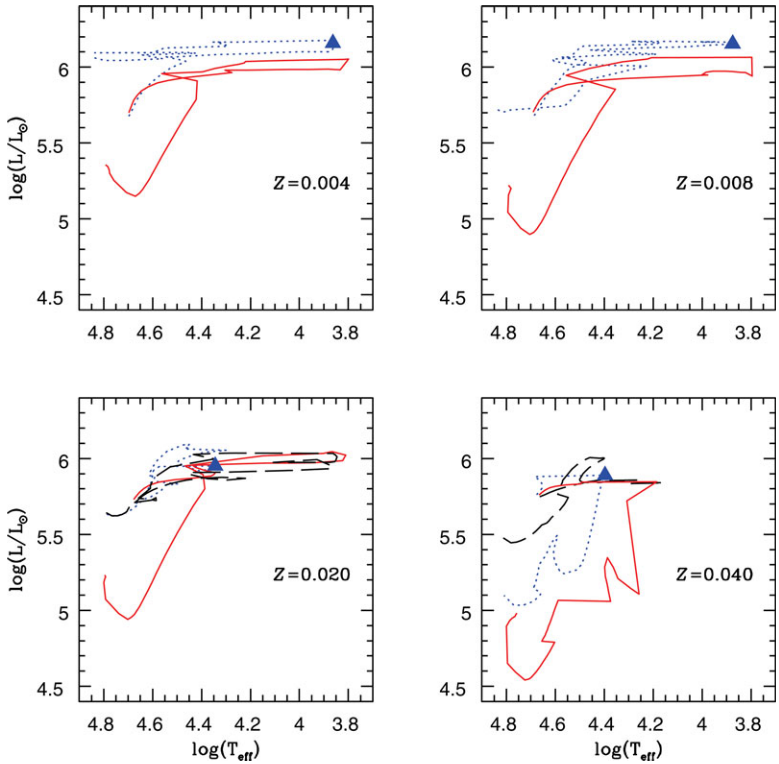

Figure 1. Comparison of the evolution of a 60 $M_\odot$ star without (solid) and with (dotted) rotation for four different metal abundances. $v_{\rm rot} = 300$ km s^{-1}. The line denotes an exploratory model with $v_{\rm rot} = 0$ and all other parameters identical to the rotating model. See Vázquez *et al.* (2007) for additional details.

2. Stellar Evolution Models with Rotation

Until the late 1990's the evolution of massive stars was thought to be determined by the chemical composition, stellar mass, and mass-loss rate, plus atomic physics and some secondary adjustable parameters. The resulting model grid led to reasonable agreement both with observations of individual stars and of stellar populations. Subsequently it was recognized that stellar rotation can play a key role in the evolution of massive stars (Maeder & Meynet 2000). Evidence of anomalous stellar surface abundances on the MS, lifetimes of certain evolutionary phases, and revised lower mass-loss rates support the concept of rotation. Rotation modifies the hydrostatic structure, induces additional mixing and affects the stellar mass loss (cf. R. Hirschi's conference contribution).

In Fig. 1 I illustrate the effects of rotation on the evolution of a 60 $M_\odot$ star. Rotation leads to generally higher luminosities and higher effective temperatures for massive stars. This is the result of the larger convective core and the lower surface opacity in the presence of rotation. (Recall that hydrogen is the major opacity source and any decrease of its relative abundance by mixing lowers the opacity and therefore increases the temperature.) Fig. 1 suggests a significant luminosity increase of a 60 $M_\odot$ star even on the MS. This trend is present in all massive stars down to ~20 $M_\odot$, depending on metallicity. The lower the metallicity, the more important the influence of rotation, which ultimately becomes the dominant evolution driver for metal-free stars (Hirschi *et al.* 2008).

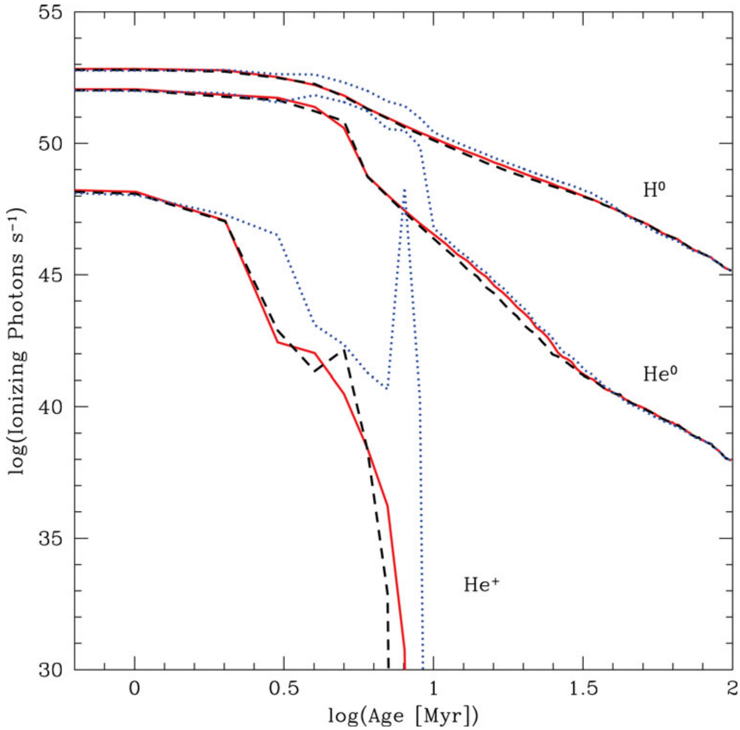

Figure 2. Number of photons in the H^0, He^0, and He^+ continuum (solar composition). Line types as in Fig. 1.

3. Revised Population Models

Vázquez *et al.* (2007) implemented the full grid of rotating evolution models into Starburst99. Stellar atmospheres and/or empirical spectral libraries were attached for each mass and at each time step. The atmospheres that were used for hot stars are those published by Smith, Norris, & Crowther (2002). For an assumed IMF one can then compute the full spectral energy distribution (SED) and its evolution with time. All models quoted here are for a Salpeter IMF with mass cut-offs at 1 and 100 $M_\odot$. The Hawaii group is independently using these SED's as input for photo-ionization modeling with the Mappings code (E. Levesque, these proceedings).

The most dramatic changes with respect to prior models occur at the short-wavelength end of the SED. The ionizing luminosities for a singular burst with mass 10^6 $M_\odot$ are shown in Fig. 2. Since the most massive stars are more luminous and hotter, their ionizing luminosities increase during O-star dominated phases ($2 - 10$ Myr). The increase reaches a factor of 3 in the hydrogen ionizing continuum and several orders of magnitude in the neutral and ionized helium continua. The predictions for the latter need careful scrutiny, as the photon escape fraction crucially depends on the interplay between the stellar parameters supplied by the evolution models and the radiation-hydrodynamics of the atmospheres. In contrast, the escape of the hydrogen ionizing photons has little dependence on the particulars of the atmospheres and consequently is a relatively safe prediction.

Luminosities for selected wavelengths and passbands are reproduced in Fig. 3. In addition to the previously discussed changes when O stars dominate, the figure suggests significant revisions at epochs when red supergiants are present ($10 - 20$ Myr). The new

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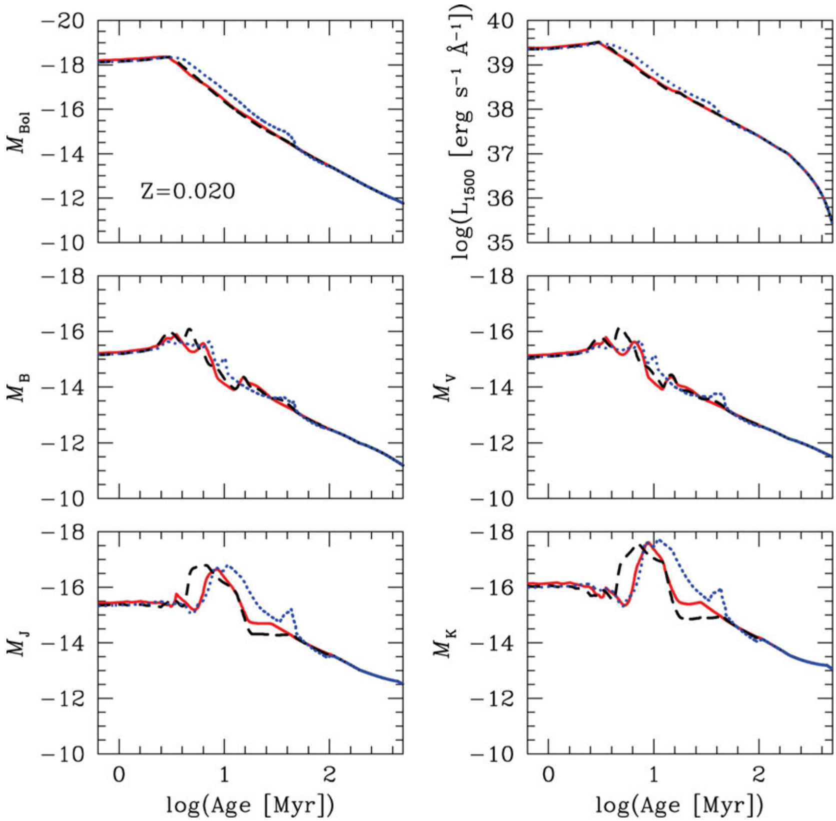

Figure 3. $M_{\rm Bol}$, L_{1500}, $M_{\rm B}$, $M_{\rm V}$, $M_{\rm J}$, and $M_{\rm K}$ vs. time. The bands most affected by the new models are those in the ultraviolet and infrared. Solar chemical composition. Line types as in Fig. 1.

evolution models with rotation predict an enhanced red supergiant phase which becomes noticeable, e.g., in the higher K band luminosity. The fact that all curves converge after ~50 Myr is an artifact: the models with rotation only reach down to a mass of 9 $M_\odot$, and the traditional tracks were used at masses below that value. However, the effects of rotation are expected to be small at these lower masses.

4. Implications for Star-Formation Indicators

The results discussed so far apply to stellar populations forming quasi-instantaneously. Choosing an instantaneous population makes it easier to identify physical processes in the SED since a particular epoch in time is usually associated with a specific stellar mass interval. While singular bursts are a good approximation for the star-formation history of, e.g., a stellar cluster, galaxies are better described by a star-formation equilibrium when stellar birth and death rates are identical. In this case one can derive relations between the star-formation rate and monochromatic luminosity independent of age.

Star-formation rates as a function of luminosity for several strategic wavelengths were determined for steady-state populations of age 100 Myr. At that epoch massive stars have reached an equilibrium for all wavelengths considered here. The IMF is the same as before. The new relations for stellar models with rotation having solar chemical composition are:

$$SFR\ [M_\odot\ {\rm yr}^{-1}] = 3.55 \times 10^{-54} N_{\rm LyC}\ [{\rm s}^{-1}] \tag{4.1}$$

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$$SFR\ [M_\odot\ \mathrm{yr}^{-1}] = 3.39 \times 10^{-41} L_{1500}\ [\mathrm{erg\ s^{-1}\ \AA^{-1}}] \tag{4.2}$$

$$SFR\ [M_\odot\ \mathrm{yr}^{-1}] = 6.31 \times 10^{-40} L_{\mathrm{V}}\ [\mathrm{erg\ s^{-1}\ \AA^{-1}}] \tag{4.3}$$

$$SFR\ [M_\odot\ \mathrm{yr}^{-1}] = 1.48 \times 10^{-44} L_{\mathrm{FIR}}\ [\mathrm{erg\ s^{-1}}]. \tag{4.4}$$

For comparison, if eqs. (4.1), (4.2),(4.3), and (4.4) were derived with the previous tracks (as currently implemented in Starburst99), the conversion factors between luminosity and star-formation rate would be 4.42×10^{-54}, 4.07×10^{-41}, 6.76×10^{-40}, and 1.78×10^{-44}, respectively. The revised relations lead to somewhat lower star-formation rates when applied to the commonly used star-formation measures. The largest effect is for the ionizing photon flux, which can be determined, e.g., from the Hα luminosity. The new rates will be about 25% lower for the same Hα luminosity. In practice, this decrease is hardly significant because other systematic uncertainties, such as the IMF scaling, are more important.

For lower metallicities, the M/L of rotating stars becomes even lower, and this trend is reflected in the M/L of the populations. Consequently the conversion coefficients in eqs. (4.1), (4.2),(4.3), and (4.4) for 20% solar composition become 2.77×10^{-54}, 3.31×10^{-41}, 5.50×10^{-40}, and 1.43×10^{-44}, respectively. The difference between the new conversion at 20% and the previous conversion at solar composition for the ionizing luminosity reaches almost a factor of 2, which is clearly non-negligible.

To summarize, we find noticeable changes in the theoretically predicted M/L ratios of stellar populations computed with the new grid of stellar evolutionary tracks with rotation. Whenever hot, massive stars contribute to the SED, the revised luminosities are higher and the spectrum is harder. The effects are subtle at optical and infrared wavelengths but significant in the ultraviolet. Single stellar populations with ages of several Myr are predicted to have ionizing fluxes that are higher by a factor of up to 3. Steady-state populations are less affected because of the diluting effect of ongoing star formation. Nevertheless, the conversion factor between Hα luminosity and star-formation rate may change by 25% or more.

A prudent Starburst99 user may want to take the new calibrations with care. While there is general consensus that the new evolution models with rotation are a quantum leap over their predecessors, these tracks are still in an exploratory stage and further testing is needed. Ultimately, the new grid and the corresponding revision of the star-formation measures will become the default in Starburst99. It is frustrating from the perspective of the evolutionary synthesis modeler that stellar rotation introduces a new free parameter that reduces some of the deterministic concepts of the previous model generation.

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