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Response to comment on "An excess of massive stars in the local 30 Doradus starburst"

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Farr and Mandel reanalyse our data, finding initial-mass-function slopes for high mass stars in 30 Doradus that agree with our results. However, their reanalysis appears to underpredict the observed number of massive stars. Their technique results in more precise slopes than in our work, strengthening our conclusion that there is an excess of massive stars above $30\,\mathrm{M}_\odot$ in 30 Doradus.

Farr and Mandel (*1*) reanalysed the results of our study (*2*), in which we investigated the star-formation history (SFH) and stellar initial mass function (IMF) of the local 30 Doradus (30 Dor) starburst in the Large Magellanic Cloud and found an overabundance of stars with initial masses beyond $30\,\mathrm{M}_{\odot}$. They use an alternative and potentially more powerful statistical framework, hierarchical Bayesian inference, and infer IMF power-law indices for massive stars that are in agreement with our results (compare the IMF slope distributions in their fig. 1 to the 1σ range inferred in our analysis). Their analysis allows them to infer the IMF slope with higher precision than was possible in our case, such that their inferred IMF slope for high mass stars in 30 Dor is shallower than that of a Salpeter IMF (*3*) with an even larger confidence (more than 95.5% compared to 83% in our analysis). Their reanalysis therefore supports our main findings and conclusions about the IMF in 30 Dor.

Farr's and Mandel's (*1*) main criticism of our work is that "[t]here is no statistical meaning to [age and mass] distribution[s] obtained" by adding the posterior probability distributions of the ages and initial masses inferred for individual stars. It is true that such distributions are not posterior probability functions in a Bayesian framework. However, we caution that the IMF is historically defined as a histogram of stellar masses (*3–9*) and our procedure to add the posterior probability distributions of the initial masses of individual stars is the equivalent of computing a histogram for the mass distribution of a sample of stars, while taking into account the observational uncertainties of individual mass estimates. Virtually all IMFs inferred in the literature are constructed in this way, so Farr's and Mandel's criticism implicitly applies to those as well. The VLT-FLAMES Tarantula Survey (VFTS) (*10*) has reached a completeness of about 73% with respect to a more complete census (*11*) of massive stars in 30 Dor (see fig. S2 in our original work). For a complete stellar sample, the age distribution of stars obtained with our method would directly provide the SFH at the youngest ages where even the most massive stars did not yet end their nuclear burning lifetime—so there is also meaning to age distributions constructed as was done in our work.

We have tested our statistical analysis with mock data. To this end, we sampled a stellar population of 1000 stars more massive than $15\,\mathrm{M}_{\odot}$ for a given Salpeter high-mass IMF with slope $\gamma = -2.35$ and a continuous SFH (constant star formation rate). In this way, we have obtained Gaussian distributions of the ages and masses of individual mock stars with 1σ uncertainties of 20% and 15% in age and mass, respectively. These uncertainties are characteristic of the age and mass uncertainties of stars in our sample of 30 Dor stars (*2*). We then used exactly the same analysis technique as in our original work to infer the IMF and SFH of the mock star sample. The results of this test are shown in Fig. 1 and demonstrate that our analysis method is able to reproduce the underlying SFH and IMF of the mock stars. For comparison, we show the distribution of initial masses for an IMF with slope $\gamma = -1.90$ to illustrate that our analysis technique can distinguish between a Salpeter IMF slope of $\gamma = -2.35$ and a shallower slope of $\gamma = -1.90$. This test further shows that both IMFs reproduce the mock data similarly well in the mass range 15–$30\,\mathrm{M}_\odot$ and that the high mass end ($> 30\,\mathrm{M}_\odot$) of the distribution of mock masses has the largest power to constrain the high-mass IMF slope (Fig. 1C).

Our analysis of the VFTS data relies on two different techniques to infer the high-mass end of the IMF: (i) by fitting the observed distribution of stars in the mass range 15–$200\,\mathrm{M}_\odot$ and (ii) by fitting the number of stars more massive than 30 and $60\,\mathrm{M}_\odot$. Both procedures give results that are in good agreement (*2*). From the inferred masses and corresponding uncertainties of our sample stars, we find $75.9^{+6.8}_{-7.0}$ stars above $30\,\mathrm{M}_\odot$ and $22.2^{+4.0}_{-4.6}$ stars above $60\,\mathrm{M}_\odot$ (*2*). Contrarily to what Farr and Mandel write in their reanalysis (*1*), their online data (https://github.com/farr/30DorIMF, as accessed on 6th May 1pm GMT) suggest that their best-fitting SFH and IMF models underpredict the observed number of massive stars. They predict on average ≈ 65 stars above $30\,\mathrm{M}_\odot$ and ≈ 18 stars above $60\,\mathrm{M}_\odot$. Their ratio of the number of stars $> 30\,\mathrm{M}_\odot$ to the number of stars $> 60\,\mathrm{M}_\odot$ (≈ 3.6) is larger than what we have observed in 30 Dor (≈ 3.4), which appears to be consistent with Farr and Mandel inferring slightly steeper IMF slopes than we did in our analysis. Indeed, using our SFH model and the results of our fitting method (ii), the numbers of massive stars above 30 and $60\,\mathrm{M}_\odot$ as predicted by Farr and

Mandel are found for an IMF slope of about $\gamma = -2.10$ (fig. 2 in our original work (*2*)). This is consistent with their best-fitting IMF slopes of $\gamma = -2.05$ to -2.15 for the different SFH models.

The reanalysis of Farr and Mandel gives systematically steeper IMF slopes than in our work and consequently seems to underpredict the observed number of massive stars in 30 Dor. We do not know the cause of this discrepancy. Our methodology appears to be robust and the only other obvious difference in the two approaches—besides the statistical framework—is the assumption on the SFH. We directly infer the SFH from the data without making assumptions on its functional form. Farr and Mandel assume Gaussian and exponential SFH models that provide more degrees of freedom than in our case, and find IMF slope differences of $\Delta\gamma \approx 0.1$ depending on the assumed SFH model. This is a systematic uncertainty that we did not discuss in our original work and that makes the inference of the IMF of composite stellar populations even more challenging.

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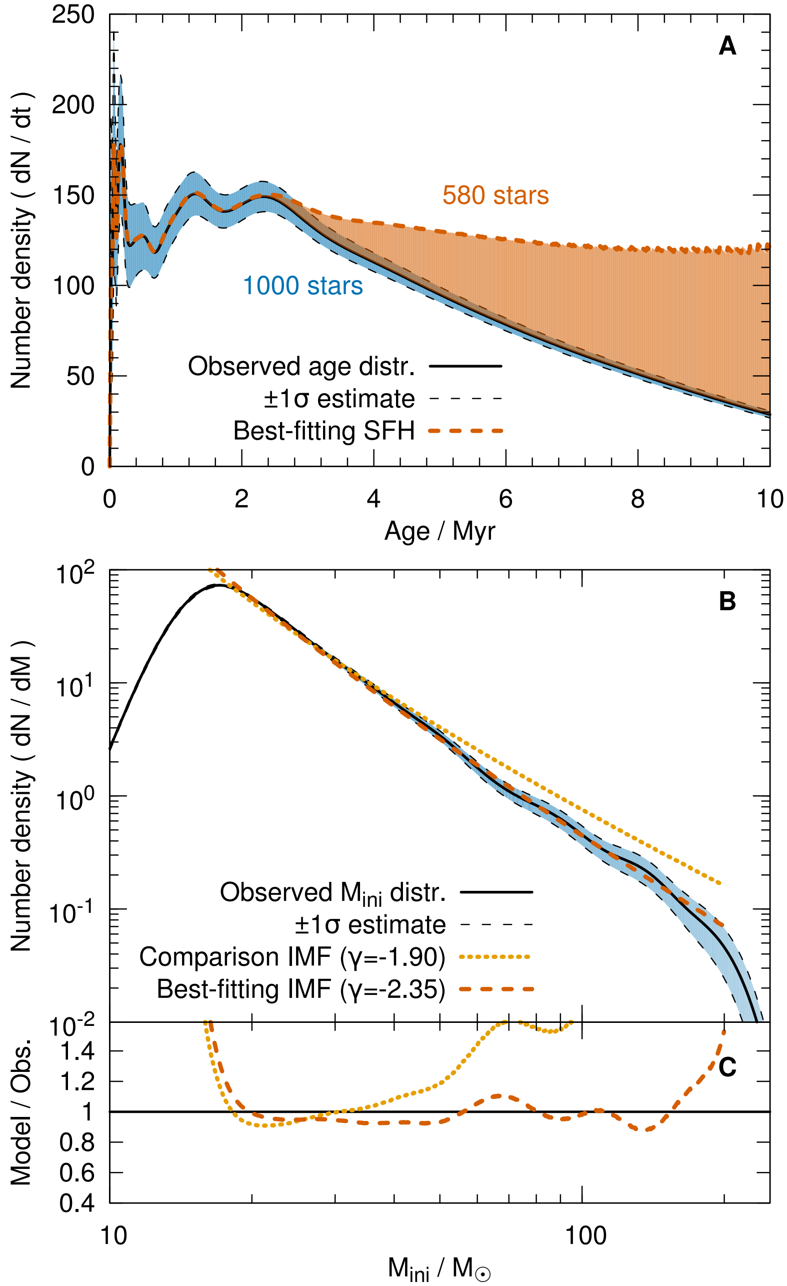

Figure 1: Inference of the SFH and IMF of a mock stellar population. Distributions of ages (A) and initial masses (B) of the mock stars (black lines) sampled from a Salpeter IMF with slope $\gamma = -2.35$ including bootstrapped 1σ estimates. The best-fitting IMF and SFH are indicated by the red dashed lines. For comparison, the predicted distribution of initial masses is shown for an IMF slope of $\gamma = -1.90$ (orange dotted line). C) Ratio of the predicted model and "observed" mock initial mass distributions, showing that the two IMF models only deviate from the mock data by more than the uncertainty above $30\,\mathrm{M}_{\odot}$.