The Evolution of Stellar Mass Density and its Implied Star Formation History

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Abstract. Using a compilation of measurements of the stellar mass density as a function of redshift we can infer the cosmic star formation history. For \( z < 0.7 \) there is good agreement between the two star formation histories. At higher redshifts the instantaneous indicators suggest star formation rates larger than that implied by the evolution of the stellar mass density. This discrepancy peaks at \( z = 3 \) where instantaneous indicators suggest a star formation rate around 0.6 dex higher than those of the best fit to the stellar mass history. We discuss a variety of explanations for this inconsistency, such as inaccurate dust extinction corrections, incorrect measurements of stellar masses and a possible evolution of the stellar initial mass function.

1. Introduction

Much contemporary research in extragalactic astronomy has revolved around the determination of the instantaneous cosmic star formation history (SFH, Lilly et al. 1996; Madau et al. 1996). Measuring this quantity from observations requires a number of assumptions, with the form of the dust obscuration corrections and stellar initial mass function (IMF, e.g., Kroupa 2007) being among the most important. Integration of the instantaneous SFH over redshift, making appropriate corrections for stellar evolution processes, yields the current stellar mass density. This quantity can be independently measured, and numerous studies have attempted comparisons of these quantities (e.g., Madau et al. 1998; Cole et al. 2001; Fontana et al. 2004; Arnouts et al. 2007). A number of studies (Eke et al. 2005; Hopkins & Beacom 2006; HB06 hereafter) also claim the instantaneous SFH overpredicts the low-redshift stellar mass density. We investigate this possible discrepancy using a compilation of the most up to date measurements of the stellar mass-density history (SMH).

A compilation of both low- and high-redshift measurements of the stellar mass density are given by Wilkins et al. (2008). Using these values we derive a best-fitting SFH, comparing this estimate to other estimates of the SFH and highlighting the discrepancies. We assume \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), \( \Omega_\Lambda = 0.7 \).

2. Comparing the SMH with the SFH

The SMH, \( \rho_\ast(t) \), can be expressed as the integral of the SFH, \( \dot{\rho}_\ast(t) \), corrected for the effects of mass-loss through stellar evolution processes such as supernovae and stellar winds. This relation may be inverted to determine the SFH from the observed evolution of stellar mass, as described by Wilkins et al. (2008).
Fig. 1 shows a best-fitting SFH derived from the SMH compilation and using the formalism of Wilkins et al. (2008), along with 1σ and 3σ uncertainty regions. For $z < 0.7$ the 1σ uncertainty region of this SFH is consistent with the best-fitting instantaneous SFH obtained by HB06. For $z > 0.7$ the best-fitting SFH of HB06 is consistently higher than that inferred from the SMH. At $z = 3$ the best fit of HB06 SFH implies a star formation rate around four times (0.6 dex) larger than that inferred from the stellar mass density.

This discrepancy suggests that either stellar mass estimates are incorrect or the SFH of HB06 is overestimated at $z > 0.7$, or perhaps both. These possibilities are explored in some detail by Wilkins et al. (2008). An alternative solution is that the larger star formation rates could be explained by an evolution of the star formation rate calibration, such as that from an evolving IMF. Investigation of an environmental or temporal evolution of the IMF has been carried out by a number of authors (e.g., Nagashima et al. 2005; Baugh et al. 2005; Le Delliou et al. 2006; Lacey et al. 2007). Fardal et al. (2007) also investigates the possibility of a different IMF in starburst galaxies to explain a discrepancy between the extragalactic background light, the instantaneous SFH and the K-band luminosity density. An IMF that produces more emission associated with instantaneous indicators (such as the UV or Hα luminosity) per unit mass created is required at high redshift. This implies evolution toward a more “top-heavy” (high-mass biased) IMF with increasing redshift. Wilkins et al. (2008) introduce such an evolving IMF. This evolution in the IMF changes the SFH implied by instantaneous indicators, the fraction of material recycled as a function of age and the observed stellar mass density. This simple model provides increased agreement between the observed SMH and that inferred from the SFH, shown in Fig. 2.

Many other forms of evolving IMF may also reproduce the relationship between the instantaneous SFH and the SFH derived from the evolution of stellar mass. The model shown here simply illustrates the effect of an increasing high-mass bias in an IMF toward high redshift, showing that such an effect is sufficient to explain the discrepancies between the instantaneous SFH and the SFH inferred from the SMH. It is likely that real stellar IMFs may have more complex evolution, and this is being investigated in ongoing work.

3. Summary

A compilation of stellar mass density measurements spanning $0 < z < 4$ was compared to the SFH, by deriving a best-fitting SFH, well described by the Cole et al. (2001) parameterisation with $a = 0.014$, $b = 0.11$, $c = 1.4$ and $d = 2.2$. There is good agreement at $z < 0.7$ between these estimates, but at progressively higher redshifts the stellar mass density and instantaneous indicator inferred SFHs become inconsistent. Instantaneous measures at $z = 3$ imply best-fitting star formation rates four times larger than those inferred from the SMH. There are a number of possible causes of this tension. These include possible systematic effects in stellar mass-density estimation, and uncertainty in the effects of dust on both stellar mass estimates and high-redshift star formation rate estimates.

A more speculative solution is an effective temporal evolution of the IMF. We have identified a simple, non-unique model for an evolving IMF that reconciles both the SFH and SMH. Other recent evidence for an evolving IMF has
Evolution of the stellar mass density

Figure 1. Comparison of the SFH inferred from the SMH compared to direct measurements. The SFH inferred from the evolution of stellar mass is shown by the 1σ and 3σ uncertainty regions (dark and light grey-shaded areas, respectively). The dark solid line is the parameterised best fit derived from the SMH. The lower panel displays the residuals from this best-fitting SFH of the other measurements. See Wilkins et al. (2008) for details.

been explored by Davé (2008) and van Dokkum (2008), who provide different parameterisations. Given the importance of both stellar mass density and star formation rate density measurements to our understanding of the galaxy formation process it is crucial that this discrepancy be resolved. To achieve this, refinements need to be made to measurements, and extensions, such as an evolving IMF, to galaxy formation models need to be implemented. Measurements of the SMH can be improved through larger and deeper surveys, more thorough understanding of dust attenuation, and improvements in population synthesis models. Improvements in the SFH can also be made by better observational constraints on dust attenuation, and independent estimates such as those from supernova rate densities, fossil-histories from local galaxies, gamma-ray bursts, and the diffuse supernova neutrino background.

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Comments
A. Renzini: A flat IMF at $z \approx 3$ would overproduce metals in galaxy clusters by a sizeable factor.
D. Wilman: It would be interesting to consider a varying IMF as a function of a physical parameter, such as the SFR. Pavel Kroupa has been suggesting recently that this might be the case.
M. Dickinson: Something physical about galaxies that affects their IMF is a more preferable driver than simply redshift. It would be useful to predict other
Figure 2. Top: The best-fitting instantaneous SFH to the compilation of HB06 obtained with a universal IMF (dotted line) compared with that obtained with an evolving IMF (solid line). Shaded regions are the 1σ and 3σ uncertainty regions. Bottom: The observed SMH assuming a universal IMF (open circles) and assuming an evolving IMF (filled circles) and corresponding predictions from the instantaneous SFH.

observable, testable properties that could be used to test any given prediction for an evolving or varying IMF.

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