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Spectral resolution is not important for modeling galaxy growth

Louis E. Abramson[1]★, Daniel D. Kelson[1], and Alan Dressler[1]

[1] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*

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ABSTRACT

We compare actual $R \sim$ **800** spectroscopy to model predictions based on galaxy star formation histories (SFHs) inferred from much lower resolution data: $ugrizJK_s$ photometry and $R \sim 25$ rest-optical prism spectra. From **XXX** systems, we find a median difference of $\lesssim$1% between all predicted and measured absorption features in the Lick index bandpasses except the Blamer lines—explainable by unmodeled emission—and Ca4227 and Fe5270 in *UVJ*-classified passive galaxies, which are 1.7%–2.5% weaker than expected. χ^2 **stuff.** As such, absent a Ca– or Fe–age prior accurate to the 2% level—whose empirical apprehension is itself a motivation for SED fitting—we find no utility in adding high resolution spectroscopy as an SFH modeling constraint, at least when using models that capture the intrinsic diversity of real growth trajectories. Our results cast doubt on the extent to which spectra from the *James Webb Space Telescope* will enhance our understanding of galaxy growth and suggest that progress requires new tactics as much as new data.

Key words: galaxies: spectroscopy

1 INTRODUCTION

A central ambition of the study of galaxy evolution is to understand stellar mass growth; i.e., galaxy star formation histories (SFHs). Spectral energy distributions (SEDs) are the key data in this work because they can be decomposed into combinations of distinct stellar subpopulations of known ages. The resulting coefficients yield the amount of stellar mass a galaxy is inferred to have formed at the lookback time corresponding to each subpopulation's age.

Different stellar subpopulations have different but not orthogonal SEDs. As such, galaxy decompositions are degenerate. Of course, those degeneracies are compounded by age-independent effects like metallicity and dust.

High resolution spectra ($R \sim 500$–5000) are often used to alleviate those degeneracies in SFH model fitting. The hope is that the absorption features that emerge in those data will increase the contrast between constituent stellar subpopulations, constrain metallicities, and yield more accurate age/mass coefficients. The utility of these data is usually taken as axiomatic, but it is also testable.

Here we present experiment that shows there is in fact little information in high resolution spectra that enhance constraints on galaxy SFHs compared to inferences based on a combination of broadband photometry and low resolution ($R \sim 25$) prism spectra.[1] We use precomputed SFH inferences based on such low resolution SEDs for a set of **XXX** systems at $\langle z \rangle$ = **ZZZ** to produce predictions of each galaxy's high-resolution spectrum. We then compare those predictions to actual high resolution ($R \sim 800$) observations taken post-facto. With the exception of the Balmer lines—whose divergence from predictions is readily ascribable to emission line infilling—we find differences to be of order **whatever they are**, suggesting **whatever we say they do**.

Section 2 describes the data on which our experiment is based, Section 3 shows the comparisons between our spectral predictions and the high resolution data, and Section 4 describes the implications of these results. We use AB magnitudes and assume a Chabrier (2003) stellar initial mass function (IMF) with $(H_0, \Omega_M, \Omega_\Lambda) = (70 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.3, 0.7)$ throughout.

2 DATA

2.1 Master sample

This experiment is based on the *Carnegie Spitzer IMACS Survey* (CSI; Kelson et al. 2014). CSI provides Magellan-IMACS Low- and Uniform-Dispersion Prism spectroscopy (**CITE**) for objects with *Spitzer* [3.5] $\leq$ 21 in **XXX sq. deg.** from **THESE FIELDS**. Combined with supplemental $ugrizJK_s$ photometry from the NEWFIRM archive (**CITE**) and Canada-France-Hawai'i Telescope Legacy Survey (CFHTLS; **CITE**), these data were used to derive flexible SFHs for each galaxy as part of the redshift estimation process. The sample is complete to $\log M_*/\mathrm{M}_\odot \sim 10.3$ at $z \sim 0.7$. The spectral resolution of the prisms varies from $R \sim$ **XXX**

★ E-mail: labramson@carnegiescience.edu

[1] A future paper will extend this statement to pure photometry-based inferences.

to $R \sim$ **YYY** at **wavelengths**, about **THIS MUCH WORSE** than the Sloan Digital Sky Survey (York et al. 2000).

Dressler et al. (2016, 2018) examine the CSI SFHs in detail. Dressler et al. (2018) provides a thorough treatment of CSI SFH quality in its Appendix. We defer the reader to those texts for that information, but briefly review the SFH inference process here. *None of these details are important in the context of the experiment we detail below*, which should be repeated using other approaches.

The CSI spectrophotometry was using 5 precomputed SEDs based on SFHs with constant star formation rates (SFRs) spanning:

- 0.0 to 0.2 Gyr prior to $t_{\rm obs}$;
- 0.2 to 0.5 Gyr prior to $t_{\rm obs}$;
- 0.5 to 1.0 Gyr prior to $t_{\rm obs}$;
- 1.0 to 2.0 Gyr prior to $t_{\rm obs}$;
- 2.0 Gyr prior to $t_{\rm obs}$ to $z = 5$;

where $t_{\rm obs}$ corresponds to the object's redshift and $z = 5$ is taken as the onset of star formation. If the data prefer, the oldest bin can also take the form of a 1 Gyr top hat starting at $z = 5$. The median redshift of the samples studied in Dressler et al. (2016, 2018) is $z \sim 0.7$, or $t_{\rm obs} \sim 7$ Gyr.

Each of the above SEDs was allowed to take an independent A_V (assuming a Calzetti et al. 2000 extinction law) but not metallicity. The latter was inferred using a prior peaked at $Z = Z_\odot$. As such, the predicted spectra do not capture the likely enrichment history of any object (cf. Pacifici et al. 2012; Morishita et al. 2019)—a fact to bear in mind as we proceed.

All spectral templates were generated using Flexible Stellar Population Synthesis (FSPS; Conroy et al. 2009) assuming default abundance patterns. When inferring the SFHs, these models—5 mass amplitudes + 5 A_Vs + 1 metallicity + 1 redshift + **1** spectrophotometry fluxing factor + **N** emission line amplitudes = **XXX** free parameters—were typically constrained by 7 + **~100** photometric + spectral datapoints. The spectral models studied below are were regenerated using the best-fit SFH parameters at $R \sim 800$ in the rest optical. Uncertainties are tabulated for the SFH bins but *not* propagated to the high resolution model spectra. As they therefore rely purely on data uncertainties, all comparisons below should be regarded as conservative.

2.2 High-resolution spectroscopy

We took high resolution data with IMACS. Dan will tell you all about it, including how many objects, and a brief description of S/N/data quality/etc.

3 CONFRONTING PREDICTIONS WITH HIGH-RESOLUTION DATA

3.1 Systematic errors

4 IMPLICATIONS

Spectral features observable in costly, high-resolution spectroscopy are readily predicted by models fit to cheaper broadband photometry and prism spectra. As such, obtaining the former seems irrelevant for investigators interested in inferring galaxy SFHs.

This fact prompts three questions: (1) Why? (2) What are the extra pixels doing? (3) What does this mean for the future? All of these relate to the difference between formal and meaningful information content.

4.1 Spectral pixels are correlated

Driving the outcomes we find is the reality that most of the pixels in high resolution spectra are physically correlated, even if they are mathematically independent. This is obvious to some extent—Balmer line depths track $B - V$ or D4000—but we find that practically all of the line information is determined by some (unknown) combination of the local and remote stellar continuum. These physical correlations should be mathematically accounted for in the SED modeling process to avoid making statements of unreasonable certainty.

The nature of this correlation is the mathematical key to understanding the SFH $\mapsto$ SED mapping, and therefore our ability to invert the latter to get at the former; i.e., execute an empirical study of galaxy evolution. This correlation is the mathematical foundation of the hypersurface characterizing the precision to which $M_*(t)$ is informatically accessible at any t as a function of data—S/N, SED sampling—and galaxy properties—sSFR, Z, σ, A_V, environment, morphology. Machine learning may be the way to illuminate this mapping.

Regardless, from an SFH inference perspective, if an SED is suitably sampled it does not need to be well sampled. What "suitable" means will be determined by the above informatic investigation, but it is clear that CSI's sampling meets or exceeds that threshold at $z \lesssim 1$, and a future paper will present evidence the 26-band UltraVista filter set (Muzzin et al. 2013) probably also does at $z \sim 0.4$.

The existence of a minimum-sampled SED suggests that it is inappropriate to treat the pixels of more densely sampled data as independent in the context of SFH inferences. By accounting for each pixel it's own degree of freedom, one produces SFHs with formal uncertainties that in no way reflect physical uncertainties. Adding sources of systematics—which may correlate the pixels—should reinflate the resultant SFH uncertainties, but that correlation may not reflect the correct physical degeneracies, which will provide a floor—perhaps a floor we have already reached—irrespective of one's ability to suppress systematics.

A likely corollary to the above is that wavelength baseline is key. Our results here suggest the high resolution details of the rest-optical if one has access, e.g., to infrared data. However, it is possible that the inverse is less true. Examining Figure 12 of Abramson et al. (2020), fits to low resolution rest-optical spectra like those from CSI used here do not predict, e.g., infrared broadband fluxes to the level the high resolution lines are reproduced here. If this statement were shown to hold using fits to the high resolution spectra also presented here, it would bear strongly on which kind of data is most critical to obtain for learning about SFHs.

4.2 Where is the information going?

The explicit science motivator for this study was inferring SFH, and, to a lesser extent, galaxy enrichment histories, which we have shown are consistent with flat to **XXX%**. However, these are not the only applications for high resolution spectroscopy, and it is in other domains where the extra pixels indeed play a role.

The trivial instance of this is in measuring emission lines, where resolution is needed to identify, e.g., embedded Balmer lines and detect subtle features like [O III] $\lambda4363$ (**cite Sanders**). Especially at low S/N, each pixel definitely counts for these applications, and estimates of, e.g., nebular extinction, ISM metallicity, or outflow properties will improve with every additional datum.

Another use that may have more bearing in the context of

SFH reconstruction is in assessing stellar velocity dispersions. Here again, each additional sampling of the wing of a line increases the certainty on that parameter (at fixed S/N). This certainty is useful because velocity dispersions are color-independent mass proxies; i.e., they are *truly* orthogonal to the information contained in the SEDs of the stellar subpopulations into which one is attempting to decompose a galaxy's SED. They might thus provide strict mass limits that could breaking some of the degeneracies mentioned in Section 1 of this text: If one knew a suitably tight relation between σ and M_*, one could apply it as a prior in the SED decomposition to constrain the amount of faint old stars that would imprint on the dispersion but perhaps not be detectable by their colors in the SED.

Unfortunately, at **0.2 dex?**, that relation likely has too much scatter to be useful. Further, allowances should be made that—due, e.g., to inside-out growth (**CITE**), the existence of thick disks, etc.—each stellar subpopulation has a different velocity dispersion, such the same degeneracies in decomposing the global σ constraint into pieces arise as did with the SED. Both of these effects would have to be marginalized over. While we do not know precisely how these effects would modulate the utility of σ as an SFH constraint, we would predict them to substantially erode it.

A yet more pertinent use would be to constrain the IMF (Conroy & van Dokkum 2012). While doing so would have no bearing on the relative accuracies of SFH inferences, it would allow all stellar masses to be placed on a firmer absolute scale, which should enhance these objects power to test simulations or first-principles theoretical predictions. Of course, if the IMF is allowed to vary with time, one encounters the same problems as with σ.

The real key is redshifts...

4.3 Future Work

5 SUMMARY

Facilities: Magellan/IMACS
Software: Python (`CarPy`).

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