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Spectral resolution is not important for modeling galaxy growth

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ABSTRACT

We compare actual $R \sim$ **800** spectroscopy to model predictions based on galaxy star formation histories (SFHs) inferred from $R \sim 25$ rest-optical prism spectra ($3700 \lesssim \lambda_{\rm rest}/\text{Å} \lesssim 5100$) and $ugrizJK_s$ photometry. From **XXX** systems, we find a median difference of ≤1% between all predicted and measured absorption features in the Lick index bandpasses except the Blamer lines—all explainable by unmodeled emission—and Ca4227 in *UVJ*-classified passive galaxies, which are 1.7%–2.5% weaker than expected. χ^2 **stuff.** These results hold using SFH models based on 5 age bins, or ones with hundreds of time steps. Therefore, absent a Ca–age prior accurate to ~2%—an object whose empirical apprehension is itself a motivation for this kind of modeling—we find no utility in adding high resolution spectroscopy as a *spectral energy distribution-related* SFH modeling constraint. Velocity dispersion-derived stellar mass constraints, may still prove useful, though intrinsic scatter and systematics must be shown to be well controlled. Assuming such issues remain, 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 more than 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 visible 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

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

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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** 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_{obs};
- 0.2 to 0.5 Gyr prior to t_{obs};
- 0.5 to 1.0 Gyr prior to t_{obs};
- 1.0 to 2.0 Gyr prior to t_{obs};
- 2.0 Gyr prior to t_{obs} to $z = 5$;

where t_{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 $t_{\mathrm{obs}} \sim 7$ 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 not physically independent, even if they are mathematically so. 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 continuum. These physical correlations should be mathematically accounted for in the SED modeling 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. Machine learning may be the way to illuminate this mapping, whose concrete output would be a hypersurface characterizing the precision to which $M_*(t)$ is informatically accessible as a function of data—S/N, SED sampling—and galaxy properties—z, sSFR, Z, σ, A_V, environment, morphology.

A first step in the above endeavor is to invert the experiment we performed here. We suspect that wavelength baseline is the underlying key to SED fitting. To test this, one could derive SFHs based on fits to the high resolution spectra presented here and try to predict the broadband fluxes well outside the rest optical. 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. The outcome of this test using high resolution spectra as a starting point would inform us as to the relative priority of broad baseline photometry vs deep spectroscopy in the study of galaxy growth. **This is crap; you always need a redshift and I think ultimately that's the trick.**

In the immediate term, the upshot is that suitably sampled SEDs need never be well sampled, at least not to understand mass growth (Section 4.2). What "suitable" means would be determined by the above investigation, but clearly CSI meets or exceeds that threshold at $z \lesssim 1$.[2] Of course, this implies that many current (and future; Section 4.3) data sets are oversampled, and that it is inadvisable to use those for SFH modeling while assuming that each pixel adds one degree of freedom. Adding systematics that correlate pixels is a minimum requirement to reinflate the resultant SFH uncertainties, but a floor will ultimately be necessary. It is very possible that we have already reached that floor.

[2] A future paper will show that the 26-band UltraVista filter set (Muzzin et al. 2013) probably also does as well at $z \sim 0.4$.

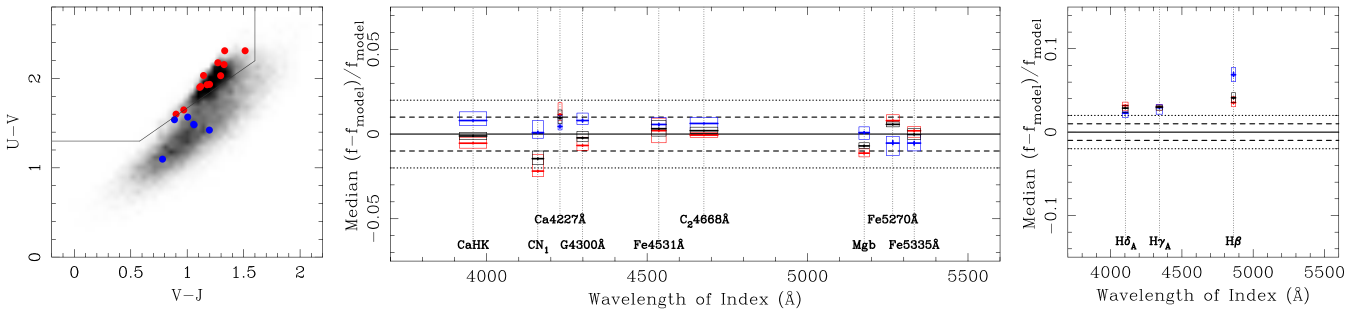

Figure 1. fit residuals, $H = 1$ SFHs

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.

Principle among these in terms of SFH reconstruction is the determination of redshift. At high resolution, the available number of constraining features is much higher than in the CSI data. **Something about the average redshift offset we find, the need to allow that to re-float when moving the predictions, whether that level of jiggle was appropriately marginalzied over in the original SFH inference, and whether that mattered.** This means that redshift–SFH covariance is stronger than it needs to be, inflating the uncertainties on the latter. Furthermore, the added uncertainty comes in key places: At CSI's spectral resolution, [O II] λ3727 is almost indistinguishable from the Balmer break. While the break has substantial leverage on the SFH, [O II] has none. A failure to resolve these may bias the SFH by implying a larger amount of A stars than is real. While we do not find this to be a critical problem (**see Figures XXX**), it does rely on accurate emission line modeling, which may be difficult in the case of ever more ubiquitous slitless spectroscopy (from HST, JWST).

Secondary in the context of SFH reconstruction is in assessing stellar velocity dispersions. Each additional sampling of a line profile increases the certainty on that parameter (at fixed S/N). This certainty is useful because velocity dispersions are color-independent mass proxies and are thus *truly* orthogonal to stellar subpopulation SEDs into which one is decomposing a galaxy SED. Velocity dispersions might thus provide strict mass limits capable of breaking some of the degeneracies mentioned in Section 1: If there existed a suitably tight relation between σ and M_*, one could apply it as a prior in the SED fitting to constrain the amount of faint old stars that would imprint on the dispersion but perhaps not be detectable in the SED.

Unfortunately, at **0.2 dex?**, that relation is probably not tight enough to be decisive. 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 paragraph on the trivial cases of emission lines and IMF?

4.3 Future Work

Don't use JWST to take high resolution spectroscopy if you're interested in stellar mass growth!

5 SUMMARY

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

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