ON THE INCORPORATION OF METALLICITY DATA INTO MEASUREMENTS OF STAR FORMATION HISTORY FROM RESOLVED STELLAR POPULATIONS

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ABSTRACT
The combination of spectroscopic stellar metallicities and resolved star color–magnitude diagrams (CMDs) has the potential to constrain the entire star formation history (SFH) of a galaxy better than fitting CMDs alone (as is most common in SFH studies using resolved stellar populations). In this paper, two approaches to incorporating external metallicity information into CMD-fitting techniques are presented. Overall, the joint fitting of metallicity and CMD information can increase the precision of measured age–metallicity relationships (AMRs) and star formation rates by 10% over CMD fitting alone. However, systematics in stellar isochrones and mismatches between spectroscopic and photometric determinations of metallicity can reduce the accuracy of the recovered SFHs. I present a simple mitigation of these systematics that can reduce their amplitude to the level obtained from CMD fitting alone, while ensuring that the AMR is consistent with spectroscopic metallicities. As is the case in CMD-fitting analysis, improved stellar models and calibrations between spectroscopic and photometric metallicities are currently the primary impediment to gains in SFH precision from jointly fitting stellar metallicities and CMDs.

Key words: galaxies: stellar content – methods: data analysis

1. INTRODUCTION

The use of color–magnitude diagrams (CMDs) of nearby galaxies with resolved stellar populations has provided a wealth of understanding of the star formation histories (SFHs) of these systems. At a high level, the relative populations of age-sensitive features such as the upper main sequence and red giant branch indicate the relative star formation rates (SFRs) at young versus old ages. Additionally, features such as the color of the red giant branch are indicative of metallicity. Thus, an examination of all age- and metallicity-sensitive CMD features can be used to infer the qualitative SFHs of these galaxies, which Hodge (1989) depicted in the form of population boxes (SFR versus lookback time and metallicity). Note that throughout this paper the SFH is defined as a combination of the SFR and age–metallicity relationship (AMR).

Quantitative approaches to this problem have been developed more recently (e.g., Gallart et al. 1996; Tolstoy & Saha 1996; Dolphin 1997; Hernandez et al. 1999; Holtzman et al. 1999; Harris & Zaritsky 2001), in which synthetic CMDs are simulated based on trial SFHs, and the quality of the fit between the observed data and a synthetic CMD is used to infer the correctness of the trial SFH. While these methods differ in terms of parameterization and CMD binning, the key similarity is that all use a quantitative metric to measure the goodness of the CMD fit.

In addition to measuring the number of stars formed as a function of lookback time, CMD fitting also provides information regarding the metallicity distribution. The most common use of photometry to infer metallicity is in the red giant branch (e.g., Da Costa & Armandroff 1990), though most features on the CMD have sufficient sensitivity to metallicity that population boxes can be estimated from the CMDs alone (e.g., Dolphin et al. 2005).

While CMD-fitting techniques are capable of estimating the AMR, inclusion of spectroscopic metallicity measurements in the solutions (de Boer et al. 2014) provides an independent, direct constraint. In addition to providing improved constraints on the AMR, this has been shown to provide a better constraint to the SFRs estimated from CMD features with age–metallicity degeneracies (e.g., Worthey 1994). Since CMD-fitting techniques are inherently self-consistent (accurately measuring SFHs of synthetic populations created from the same models), this increased precision is potentially obtained without sacrificing accuracy.

The presence of increased constraints on the solution, however, must be examined to ensure that the resulting solution is robust. As demonstrated by Dolphin (2012), even CMD-only solutions can be sufficiently constrained that the presence of systematic errors (e.g., differences between underlying stellar models) produces a solution that is inconsistent with the input SFH. Incorporating metallicity information into a solution may compound this discrepancy. For example, consider the case in which the metallicity of a real star has been measured, but where no combination of other physical parameters (e.g., age, extinction), given this metallicity, causes an isochrone to overlap the star’s CMD location.

This analysis seeks to evaluate the potential for improving SFH estimates by inclusion of metallicity information in a CMD solution, assess the magnitude of errors that can be created by systematic uncertainties, and propose a robust approach to minimize such errors.

2. INCORPORATION OF METALLICITY DATA

For stars for which both metallicity measurements and photometry are available, the CMD-fitting technique commonly used for SFH measurements can be extended by adding a third dimension to the solution, resulting in a color–magnitude–metallicity diagram (CMMD). However, this is likely to result in a large amount of data being discarded, as the photometric and spectroscopic samples are unlikely to consist of the same stars. Both conditions (stars in only photometric or only spectroscopic data) must be considered.
Stars present only in the photometric sample are the simpler case. These are often dim stars that have adequate signal-to-noise ratio for photometric measurements but not for spectroscopic determinations of metallicity. For example, many nearby galaxies have Hubble Space Telescope (HST) photometry that is significantly deeper than the spectroscopic samples, such as Milky Way companions with photometry reaching the ancient main-sequence turnoff but stellar metallicities only for red giants. To account for these stars, an extra metallicity bin can be added to the CMMD to include those stars with photometric data only. In order to create the synthetic CMMD, one must also define a metallicity completeness function that provides the probability of a star having a metallicity measurement. For the examples shown in this study, this is a simple function of color and magnitude.

The other special case for consideration is stars for which metallicity measurements are available but not for spectroscopic determinations of metallicity. For example, many nearby galaxies have Hubble Space Telescope (HST) photometry that is significantly deeper than the spectroscopic samples, such as Milky Way companions with photometry reaching the ancient main-sequence turnoff but stellar metallicities only for red giants. To account for these stars, an extra metallicity bin can be added to the CMMD to include those stars with photometric data only. In order to create the synthetic CMMD, one must also define a metallicity completeness function that provides the probability of a star having a metallicity measurement. For the examples shown in this study, this is a simple function of color and magnitude.

The population in Figure 1 is intended to represent a nearby early-type galaxy for which the photometry was obtained from a smaller field of view than the CMD; for the examples shown in this study the synthetic MDF is normalized to contain the same total number of stars as the observed MDF.

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It is important to note that the SFH measurements presented in Figures 1 and 2 are for a best-case situation in which the stellar models are perfect. Thus, these results confirm findings from Dolphin (2002) showing that excellent SFR and AMR recovery is possible with CMDs alone, and thus that inclusion of metallicity data should not be expected to provide a significant improvement.

3. EFFECTS OF ISOCHRONE UNCERTAINTIES

While the examples shown in Section 2 provide encouragement that metallicities can be used to improve SFH solutions, those examples do not incorporate any effects of isochrone uncertainties (e.g., input physics, rotation, bolometric corrections). While isochrone uncertainties are important to consider in CMD-fitting studies (Aparicio & Hidalgo 2009; Dolphin 2012), it is generally possible to obtain a good CMD solution in the presence of isochrone mismatches by allowing for an offset in age or metallicity. This is not necessarily the case in a CMMD solution, however, as it is possible that the isochrones corresponding to the measured metallicity may not fall at the CMD location of the measured photometry. In this case, finding an acceptable fit may be impossible. The solutions shown in Figures 1 and 2 did not include isochrone uncertainties, because the Padua models (Marigo et al. 2008; Girardi et al. 2010) were used both to create the simulated data and to measure the SFHs. In contrast, Figure 3 shows the same simulated data, but this time using the PARSEC models (Bressan et al. 2012) to measure the SFHs. Note that the only source of error introduced here is in the isochrones; other sources of error such as imperfections in photometric error or internal reddening models are not reflected.

Panel (a) in Figure 3 shows the systematic errors in the CMD solution, which are consistent with what was shown by Dolphin (2012). From panels (b) and (c), however, one sees that incorporation of metallicity information creates larger errors in the measured SFRs, in the sense that all star formation between 1.5 and 6 Gyr ago was pushed into a burst of age $\sim$1.5 Gyr. In effect, a CMD-only solution will tend to select isochrones with close to the correct age by using incorrect metallicities. However, once metallicity constraints are added, this is not possible and the SFRs will be in error.

In Figure 3, the systematic error in the CMMD solution is also seen to be worse than that in the CMD-only and CMD + MDF solutions. This is due to the fact that metallicities are assigned to specific stars on the CMD rather than generally to a MDF, making it more likely that stars cannot be fit by any isochrone in the set. The goodness-of-fit measurements of the solutions also indicate that the CMMD solution suffered the most degradation from the systematic errors.

4. MITIGATION OF ISOCHRONE UNCERTAINTIES

Given the risk of CMMD (or CMD+MDF) solutions introducing large systematic errors, one must carefully consider how to incorporate metallicity information. The approach proposed in this section is motivated by the observation in Section 3 that CMD fitting will account for isochrone errors by adopting metallicities shifted from the true metallicities.

When creating synthetic metallicity estimates, the synthetic metallicity can be biased relative to the metallicity of the isochrones used to populate the CMDs. That is, the metallicity error model does not need to have a mean of zero, but instead can have a mean that is a function of various parameters (the software...
used in this study allows variation with color, magnitude, and age. Note that increasing the random component of the error model would also be appropriate, though it is not done in the example shown here.

Using this approach, the synthetic data that resulted in a significant SFH error in Figure 3 were re-solved using an age-dependent metallicity offset. Note that this offset was obtained empirically by minimizing the fit parameter, not by a more detailed comparison of the two isochrone sets (which would be possible for simulated data but not for real data). Results of this solution are shown in Figure 4.

Because it is based on the CMD only, Figure 4(a) is the same solution from Figure 3, except with the age-dependent metallicity shift added. The other two panels, however, show significant improvements in the SFH solutions, with both the metallicities and SFRs much closer to the input (dashed line) than was the case in Figure 3. Specifically, the artificial 1.5 Gyr old burst was reduced by ~25%, and the bias toward measuring stars at younger ages has been reduced. By comparison with the CMD-only solution, it appears that the metallicity shifts have mitigated the additional systematic errors created by incorporating metallicity information into the solutions. In effect, the result is that the measurement of SFR versus time is largely unaffected, while the AMR has been shifted from an isochrone scale to a spectroscopic metallicity scale.

Despite having mitigated the additional error created by incorporating metallicity data, the measured SFHs are still affected by systematic errors comparable to those from CMD-only solutions. Furthermore, the SFR error bars in Figures 3 and 4 are approximately half the size of those in Figure 2. This is a result of systematic differences between the isochrone sets artificially constraining the solution space. Thus, it is necessary to include systematic uncertainties when reporting SFHs, because isochrone uncertainties affect both the measured SFH and the random uncertainties.

A final observation is that, despite incorporating knowledge of metallicities of specific stars in the CMD, the CMMD solution in Figure 4(b) is not significantly different from the CMD+MDF solution in Figure 4(c). Also, considering that the CMMD solution requires an order of magnitude more runtime and is more vulnerable to systematics (as seen in Figure 3), the recommended method to incorporate metallicities into a SFH measurement is to fit an MDF along with the CMD solution rather than to add an extra dimension to create a CMMD. Note that this is merely a separation of a CMMD into a CMD and an MDF (separating metallicity data from photometric data); modeling issues such as the selection model are unchanged.

5. SUMMARY

Incorporation of metallicity information into CMD-based SFH measurements has the potential to increase the constraints on the measured SFH, with both the SFR and AMR seeing comparable reduction in uncertainties. In this study, a three-mode approach to ensure that all data are incorporated is proposed: a single SFH solution using a CMMD for stars with photometry and metallicities, a CMD for stars with photometry only solutions. Furthermore, the SFR error bars in Figures 3 and 4 are approximately half the size of those in Figure 2. This is a result of systematic differences between the isochrone sets artificially constraining the solution space. Thus, it is necessary to include systematic uncertainties when reporting SFHs, because isochrone uncertainties affect both the measured SFH and the random uncertainties.

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only, and an MDF for stars with metallicities only. This will enable optimal solutions to be obtained in the most common cases where the spectroscopic and photometric fields are of different depths or cover different fields of view.

While incorporation of additional data creates a more tightly constrained problem, the results shown in Figure 3 show that this can create undesirable results in the particular application of measuring SFRs. Specifically, while adding spectroscopic metallicity measurements to photometry creates more precise estimates of stellar ages, uncertainties in stellar models make these age estimates less accurate than those using photometry only. Thus, a straightforward incorporation of metallicity measurements into a CMD-fitting code is likely to increase the precision but degrade the accuracy of the measured SFHs.

An approach to mitigating this error is proposed in Section 4. At its core is a mapping of isochrone metallicities to measured (spectroscopic) metallicities, which can be estimated empirically by finding the mapping that maximizes the goodness of fit. This is shown to produce SFHs whose SFRs are as accurate as those obtained from CMD-only fits, while the AMRs are consistent with the spectroscopic data. Note that this mitigation does not eliminate or even reduce systematic errors inherent in CMD-based SFH measurements (Dolphin 2012); it only mitigates the increased systematic errors caused by incorporating metallicities into the solutions. The primary benefit of incorporating spectroscopic metallicity data into SFH solutions is that the resulting AMR is consistent with spectroscopic rather than photometric metallicity measurements.

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REFERENCES

Aparicio, A., & Hidalgo, S. L. 2009, AJ, 138, 558
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Da Costa, G. S., & Armandroff, T. E. 1990, AJ, 100, 162
de Boer, T. J. L., Tolstoy, E., Lemasle, B., et al. 2014, A&A, 572, 10
Dolphin, A. 1997, NewA, 2, 397
Dolphin, A. E. 2002, MNRAS, 332, 91
Dolphin, A. E. 2012, ApJ, 751, 60
Dolphin, A. E., Weisz, D. R., Skillman, E. D., et al. 2005, in Resolved Stellar Populations, ed. D. Valls-Gabaud, & M. Chavez (Cancun, Mexico) (arXiv:astro-ph/0506430v1)
Gallart, C., Aparicio, A., Bertelli, G., & Chiosi, C. 1996, AJ, 112, 1950
Girardi, L., Williams, B. F., Gilbert, K. M., et al. 2010, ApJ, 724, 1030
Harris, J., & Zaritsky, D. 2001, ApJS, 136, 25
Hernandez, X., Valls-Gabaud, D., & Gilmore, G. 1999, MNRAS, 304, 705
Hodge, P. 1989, ARA&A, 27, 139
Holzman, J. A., Gallagher, J. S., Cole, A. A., et al. 1999, AJ, 118, 2262
Marigo, P., Girardi, L., Bressan, A., et al. 2008, A&A, 482, 883
Tolstoy, E., & Saha, A. 1996, ApJ, 462, 672
Worthey, G. 1994, ApJS, 95, 107