INTEGRATED STELLAR POPULATIONS: CONFRONTING PHOTOMETRY WITH SPECTROSCOPY

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ABSTRACT

We investigate the ability of spectroscopic techniques to yield realistic star formation histories (SFHs) for the bulges of spiral galaxies based on a comparison with their observed broadband colors. Full spectrum fitting to optical spectra indicates that recent (within $\sim 1$ Gyr) star formation activity can contribute significantly to the V-band flux, whilst accounting for only a minor fraction of the stellar mass budget which is made up primarily of old stars. Furthermore, recent implementations of stellar population (SP) models reveal that the inclusion of a more complete treatment of the thermally pulsating asymptotic giant branch (TP-AGB) phase to SP models greatly increases the NIR flux for SPs of ages $0.2$–$2$ Gyr. Comparing the optical–NIR colors predicted from population synthesis fitting, using models which do not include all stages of the TP-AGB phase, to the observed colors reveals that observed optical–NIR colors are too red compared to the model predictions. However, when a 1 Gyr SP from models including a full treatment of the TP-AGB phase is used, the observed and predicted colors are in good agreement. This has strong implications for the interpretation of stellar populations, dust content, and SFHs derived from colors alone.

Key words: galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

A detailed understanding of the stellar populations (SPs) that make up the integrated spectral energy distributions (SEDs) of both local and distant galaxies can provide important constraints for models of galaxy formation. However, confronting observations with SP synthesis models for the purpose of translating the former into physical parameters is not without significant challenges. While SP modeling has seen tremendous progress over the past decade (e.g., Bruzual & Charlot 2003, hereafter BC03; Le Borgne et al. 2004; Maraston 2005, hereafter Mar05; Schiavon 2007), misinterpretations in the data–model comparison is in order. Accounting for the TP-AGB is accomplished in Mar05 through empirical calibration to LMC globular clusters, which have independent age and Z measurements. Alternatively, synthetic model tracks can be used. The recent tracks of Marigo & Girardi (2007), whose predictions are in good agreement with those of Mar05, account for nine evolutionary stages (including the C-, M-type, and superwind mass loss phases) in the TP-AGB. (Note that the older tracks used in the BC03 models account for only a single evolutionary stage for each evolutionary phase in the TP-AGB.) In these models, the TP-AGB phase is active in SPs of ages $\sim 0.3$–$2$ Gyr and contributes significantly to the NIR flux (accounting for up to $\sim 80\%$ of the NIR flux), leading to very red optical–NIR colors for this age range. These models have already been used to resolve the uncomfortably large stellar masses and old ages derived for high-$z$ galaxies using models which do not account for all phases in their treatment of the TP-AGB phase (Maraston et al. 2006).

In the meantime, full spectrum fitting techniques have proven to be effective at recovering the underlying stellar content of integrated galaxy spectra (e.g., Heavens et al. 2000; Cid Fernandes et al. 2005; Walcher et al. 2006; MacArthur et al. 2009, hereafter Mac09). This type of analysis provides a stochastically sampled SFH for a given integrated spectrum and allows for true average, as opposed to single SP-based, age and Z estimates. Full spectral fitting is typically limited to optical wavelengths, as set by the observations. However, as most models provide SEDs in the UV–FIR range, one can use such model fits to make predictions for the galaxy light in other wavelength regions. For example, a comparison of predicted versus observed optical–NIR colors could provide valuable insight into both the reliability of the spectral fits as well as any shortcomings of the SP models themselves. This is precisely the approach we carry out here using our analysis of Gemini/GMOS long-slit spectra of local spirals (Mac09) and new optical imaging for the same galaxies from the Palomar Observatory and NIR imaging from the Two Micron All Sky Survey (hereafter 2MASS; Skrutskie et al. 2006). As we are interested in predictions from models that use different treatments of the TP-AGB phase, we focus on two galaxies from our spectroscopic sample (NGC 628 and UGC 2124) with the highest quality data and whose derived SFHs indicate significant
contribution (in $V$-band light-weight) from a 1 Gyr SP, i.e., where the TP-AGB NIR signature is expected to be strong.

2. DATA

The long-slit spectroscopic data used for this study, from Mac09, were collected with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on the 8 m Gemini North telescope. The GMOS detector and B600 grating combination provides a spatial resolution of 0.072 pixel$^{-1}$ and a dispersion of 0.45 Å pixel$^{-1}$. The slit field of view (FOV) of 5' × 2' provided a boxcar width = 10.81 Å resolution. The spectral coverage spans ~4050 – 6750 Å.

Optical imaging in the $BVRi$ Bessel filters was collected at the Palomar 200 inch telescope in 2006 December. The Large Format Camera consists of a six CCD mosaic with a FOV of 6' × 12' per CCD. Our galaxies have optical diameters ≤10.5', leaving enough room beyond the optical radius on a single chip for sky measurements. Typical exposure times were 1–2 minutes and 2' × 2' binning gave 0.363 pixel$^{-1}$. The seeing ranged from FWHM = 1'8 – 3'7. The data were bias-subtracted and flat-fielded using a combination of night sky and dome flats to carefully account for both the high-frequency spatial sensitivity (dome) and the large-scale illumination (sky) of the chip. Due to the bright-moon conditions, it was necessary to model the background with a surface. This induced a typical sky error of ~0.01 mag. The data were calibrated following the technique of Courteau (1996) using stars from several Landolt fields (Landolt 1992), for typical calibration errors of ~0.03 mag.

Imaging in the NIR $JHKs$ filters were obtained from the 2MASS online database. The background levels were carefully re-measured for each image and the photometric zero points were taken from the 2MASS headers.

All data (imaging and spectroscopic) were corrected for Galactic foreground extinction (Schlegel et al. 1998).

2.1. Radial Extractions

In order to make a direct comparison between information gleaned from optical spectra versus broadband imaging, we must compare the spectral fits with colors from the same effective radial bins. As such, rather than the usual azimuthal extraction of SB profiles (e.g., Courteau 1996; MacArthur et al. 2003), profiles were extracted from all bands ($BVRiJHKs$) using the same position angle and slit width as for the GMOS observations. We accounted for differences in the observed point-spread functions by convolving all profiles (imaging and spectroscopic) with the largest FWHM of all observations for each galaxy. Finally, radial binning for both the imaging and spectroscopy was set to the largest measured dispersion, which is that of 2MASS (1' pixel$^{-1}$).

3. AGE, METALLICITY, AND SFH FROM POPULATION SYNTHESIS

The SP fitting technique used here is as described in Mac09; a brief summary is provided below. Our “full population synthesis” technique consists of a bound constrained optimized fit representing the relative contribution of each of the 70 model templates to the observed spectrum. The only fixed bound is that of no negative template contributions. The templates are from the BC03 models which provide SEDs representing simple stellar populations (SSPs), i.e., single bursts of star formation (SF) at a given age and $Z$, at a resolution of ~3 Å FWHM.$^6$ The selected library of 70 SSP templates covers the age range 0.001–20 Gyr and metallicities of $Z = 0.0004$–0.05 and we use the models with the Chabrier (2003) initial mass function. Our procedure also allows for dust reddening to the observed SED according to the prescription of Charlot & Fall (2000). See Mac09 for details. To accommodate any non-stellar contributions to the observed spectrum not considered in the BC03 models, we used an iterative masking scheme whereby deviant [data–model] points are given zero weight in the fit.

$^6$ Although see Section 3.4.1 of Mac09 for a detailed analysis of the true resolution of these models.
Figure 1 shows the full population synthesis fits to the central spectra of NGC 628 and UGC 2124 (extracted as described in Section 2.1), and in Figure 2 we plot the inferred SFHs from the fits. In Table 1, we list for each galaxy the percent light and mass contributions of “very young” (0.001–0.4 Gyr), “young” (1–2 Gyr), “intermediate” (4–7 Gyr), and “old” (10–20 Gyr) age SSPs to the fits.

For both galaxies there is a contribution from 13–20 Gyr SSPs.7 While their weight in light may not seem dominant, these old populations contribute 74% and 93% to the stellar mass budget of NGC 628 and UGC 2124, respectively (Table 1). However, we are particularly interested here in a significant contribution from SSPs that would be expected by the Mar05 models to have NIR excesses from their treatment of the TP-AGB stellar evolution phase. The age range for which the signature is present is highlighted by the gray shading in Figure 2 and referred to as “young” in Table 1. The contribution to the V-band normalized light of the young population of interest is 67% and 33% for NGC 628 and UGC 2124, respectively. Thus, if our SFHs are reliable, according to the Mar05 models, these galaxies would be expected to show signs of the TP-AGB NIR excess.8

4. “PREDICTED” VERSUS OBSERVED OPTICAL–NIR COLORS

The full population synthesis fits to the spectra are constrained by the observed 4050–6750 Å region (gray shading in Figure 3) and, modulo emission lines, represent this region very well (see Figure 1). Since the BC03 models cover the range 90 Å – 160 μm, we can use the model fits to “predict” colors in other bands. Any difference between colors predicted in this way, in any given integrated spectrum; inadequacy of the template library to represent the full coverage of SP age and Z in any given integrated spectrum; unrealistic estimate of the dust extinction from the population synthesis fits; errors in the SP modeling predictions outside the optical range due to, for example, errors in the stellar evolutionary physics.

To test for any discrepancies, we now compare the predicted optical–NIR colors from the full population synthesis BC03 model fits to the observed colors. A direct estimate of the predicted NIR excess is complicated by a number of issues related to differences between the BC03 and Mar05 models. First, for a given age and Z, the model predictions are not identical, even within the optical limits of our spectra. Second, the SEDs provided in each model do not cover precisely the same age/Z grid. To illustrate differences between the BC03 and Mar05 model SEDs, we compare in Figure 3 the 1 Gyr/Z = 0.05 SSP from BC03, which contributes significantly to both SFHs in Figure 2, to the SED closest in age and Z from the Mar05 models (1 Gyr/Z = 0.04). While most of the difference is attributable to the different treatments of the TP-AGB phase between BC03 and Mar05, some of it could also be due to the overall larger contribution of AGB stars in the Mar05 models.

Given the above caveats, we now look at the observed versus predicted optical–NIR colors for NGC 628 in Figure 4. In all color combinations, the model fits (open triangles) predict colors that are too blue compared to the observed (solid triangles) optical–NIR colors. The arrows represent the difference in color between the BC03 1 Gyr/Z = 0.05 SSP and the Mar05 1 Gyr/Z = 0.04 SSP. Indeed, the vectors represent the data–model difference very well. For UGC 2124 in Figure 5, it appears that a steeper vector would be required to precisely match the data–model difference. In Mac09, we demonstrated by a comparison of absorption-line indices that there is evidence of an enhanced [α/Fe] SP in the bulge region of UGC 2124 (see Figure 4 in Mac09), which could also affect the observed colors (only solar-scaled abundance ratio models are considered here).

To assess whether abundance ratios could compensate for the extra steepness in the data–model difference, we also plot in Figure 5 a gray vector (green in online version) which represents the effect of a super-solar abundance ratio star at a given $T_{\text{eff}}/\log(g)/Z$ from the synthetic stellar models of Coelho et al. (2005) (see the figure caption for details). The Coelho models do not extend far enough into the NIR for an accurate K-band estimate. A combined effect of both TP-AGB treatment and super-solar

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**Table 1**

Percent Contributions of all SSPs in Given Age Ranges (Very Young = 0.001–0.4 Gyr; Young = 1–2 Gyr; Intermediate = 4–7 Gyr; Old = 10–20 Gyr) to Full Population Synthesis Fits Weighted by Light (V-band normalized) and Mass

| Name  | Light Weight | Mass Weight |
|-------|--------------|-------------|
|       | 0.001–0.4 Gyr | 1 Gyr       |
|       | 1–2 Gyr      | 2 Gyr       |
|       | 4–7 Gyr      | 5 Gyr       |
|       | 10–20 Gyr    | 10 Gyr      |
| N0628 | 7            | 63          | 1          | 25         | 0          | 74         |
| U2124 | 0            | 33          | 67         | 67         | 7          | 93         |

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7 We are not concerned here with model ages that are older than the age of the universe as absolute model SSP ages are not precisely calibrated.

8 Note that we did not perform the population synthesis fits with the Mar05 models as they have a lower resolution than BC03, thus reducing the predictive power of the spectra to disentangle the high frequency features in the fitting process. A direct comparison between fits using different models awaits the release of higher resolution models.
Figure 4. Color–color plots for NGC 628. The open triangles (red in online edition) are colors measured (“predicted”) from the BC03 model full population synthesis fits to the observed central spectrum. The solid triangles are the corresponding observed colors. Observational errors (calibration and sky subtraction) are indicated at lower right. Overplotted are grids of BC03 models with exponential SFHs (see MacArthur et al. 2004 for details). Solid and dashed lines are iso-Z and iso-age, respectively, with darker shading indicating higher Zs and older ages; see middle bottom panels for labels of average age and Z. Arrows at lower left (blue in online edition): model prediction differences between the 1 Gyr/\(Z = 0.05\) BC03 SSP (red dashed curve in Figure 3) and the Mar05 1 Gyr/\(Z = 0.04\) SSP (solid blue curve in Figure 3). The arrows point toward the Mar05 predictions (from their respective location for the BC03 models).

(A color version of this figure is available in the online journal.)

Figure 5. Same as Figure 4, but for UGC 2124; the gray arrows (green in online edition) show the effect of a non-solar abundance ratio SSP on the colors. Specifically, this represents the difference between \([\alpha/Fe] = 0.4\) and \([\alpha/Fe] = 0\) stars with \(T_{\text{eff}} = 4000\) K, [Fe/H] = solar, log(\(g\)) = 3.0 from the models of Coelho et al. (2005).

(A color version of this figure is available in the online journal.)

\([\alpha/Fe]\) would be represented by the addition of the two vectors and resulting in a steepening that more closely accounts for the data/model offsets.

As a further check on the model predictions, we plot in Figure 6 NIR–NIR colors for both galaxies. Again we see a difference between the observations and model predictions, but not in the same sense as the optical–NIR colors. While the \(J−H\) color is predicted to be redder in the Mar05 models, the \(J−K\) and \(H−K\) colors are predicted to be bluer. As for the optical–NIR colors, the Mar05 models could account for these differences. The only mismatch is in the \(H−K\) versus \(J−H\) colors for UGC 2124, but this could very well be another manifestation of \([\alpha/Fe]\)-enhanced SPs (whose predictions do not extend far enough to test this).
5. DISCUSSION

The above analysis has important implications for the modeling and interpretations of integrated stellar populations. The full population synthesis fitting of NGC 628 and UGC 2124 indicates the presence of a young component (≈1 Gyr, where Mar05 and BC03 model predictions differ significantly) contributing ≈50% to the V-band flux. In SPS models which account for a detailed treatment of all stages of the TP-AGB stellar evolution phase, this young population would contribute a significant amount of NIR flux, resulting in very red optical–NIR colors, a mild reddening in $J - H$, and a bluing of the $H - K$ and $J - K$ colors. All of these predicted trends were confirmed with the observed colors, thus providing further support for the presence of the young component, in addition to strongly favoring the contribution of the TP-AGB phase used in the Mar05 SPS models (as well as the Marigo & Girardi 2007 models which agree well with the Mar05 predictions).

Such anomalous colors have been reported before. For a sample of 5800 galaxies from the SDSS, Eminian et al. (2008) compared optical and NIR colors with quantities derived from spectra (star formation rate (SFR), age, $Z$, and dust attenuation). They found that galaxies with higher SFRs, while having bluer optical colors ($g - r$), also had redder NIR colors ($H - K$), which they interpreted as being in qualitative agreement with the dominance in NIR light of the TP-AGB phase after a burst of SF.

At higher redshift, Ellis et al. (2001) observed the colors of bulges out to $z \sim 1$ and found that, while many of the bulges had blue optical colors, consistent with recent SF, at $z \gtrsim 0.5$, the same bulges had red observed $J - H$ colors. At these higher redshifts, this translates roughly into rest-frame $i - J$. Indeed, while the Mar05 models only show a mild reddening compared to those of BC03 of the $J - H$ color (by ≈0.1 mag for a solar 1 Gyr SSP), the $i - J$ color is much redder (by ≈0.7 mag), thus explaining why the effect is only observed at higher $z$. While Ellis et al. attributed the red NIR colors to a predominantly “short burst” mode of bulge building at high $z$, the red NIR colors could also be explained by the presence of young SPs in the active TP-AGB phase.

These results indicate that caution must be taken when interpreting the optical–NIR colors of integrated stellar populations. Red colors have typically been interpreted as being due to some combination of old age, high $Z$, and significant dust extinction. However, we have shown here that some of the redness could actually be due to a significant contribution to the SED from a young SP with significant NIR flux excess from the TP-AGB evolutionary phase. Further, confirmation of this result and its implications awaits larger samples and analysis with forthcoming higher-resolution implementations of the SP models which include proper treatment of the TP-AGB stellar evolutionary phase.

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