EMISSION CORRECTIONS FOR HYDROGEN FEATURES OF THE GRAVES ET AL. SLOAN DIGITAL SKY SURVEY AVERAGES OF EARLY-TYPE, NON-LINER GALAXIES

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ABSTRACT

For purposes of recovering correct absorption line strengths for stellar population analysis, emission corrections for Balmer series indices on the Lick index system in Sloan Digital Sky Survey (SDSS) stacked quiescent galaxy spectra are derived as a function of the Mg b index strength. These corrections are obtained by comparing the observed Lick index measurements of the SDSS composite spectra with new observed measurements of 13 Virgo Cluster galaxies, and checked with model grids. From the Hα–Mg b diagram, a linear correction for the observed measurement is constructed using best-fit trend lines. Corrections for Hβ, Hγ, and Hδ are constructed using stellar population models to predict continuum shape changes as a function of Mg b plus Balmer series emission intensities typical of H ii regions. The corrections themselves are fairly secure, but the interpretation for Hδ and Hγ indices is complicated by the fact that the Hδ and Hγ indices are sensitive to elemental abundances other than hydrogen.

Key words: galaxies: abundances – galaxies: clusters: individual (Virgo cluster) – methods: analytical – surveys

1. INTRODUCTION

One of the more important factors in determining the age of a stellar population, such as an elliptical galaxy, is being able to measure the hydrogen Balmer series (Worthey 1994; O’Connell 1976). The first two Balmer lines, Hα and Hβ, are primarily used to determine the age of a stellar population because of their relative insensitivity to changes in metallicity (Serven et al. 2005; Korn et al. 2005) making a measurement of these two lines a more reliable estimator of age than the higher-order Balmer lines Hγ and Hδ, which are sensitive to changes in metallicity (Serven et al. 2005; Korn et al. 2005) making knowledge of the relative abundances of elements in a given spectra necessary in order to get a consistent agreement of ages from all the Balmer lines.

An additional, contrary, observational factor in determining the age of a galaxy is nebular hydrogen emission, which can give the impression of a much older galaxy by filling in and weakening the diagnostic Balmer absorption features. In the past, an emission correction based on the [O ii] λ3727 or [O iii] λ4959, 5007 emission lines (Schiavon et al. 2006; González 1993) was used, in which the difference in the measured equivalent width (EW) of a hydrogen line such as Hα or Hβ due to emission is some fraction of the EW of [O ii] or [O iii]. However, the correlation between hydrogen and oxygen emission strengths is weak, and indeed there is no apparent astrophysical reason why the two should be tightly correlated. On the other hand, being able to use hydrogen recombination lines, which have ratios that are nearly fixed with respect to themselves (Osterbrock & Ferland 2006), should give a more reliable result.

Toward that end, we compare 13 high-quality spectra of Virgo Cluster early-type galaxies (J. Serven & G. Worthey 2010, in preparation) with a sample of Sloan Digital Sky Survey (SDSS) spectra from Graves et al. (2007). The Virgo Cluster elliptical galaxies consist of 13 red galaxies with colors 0.75 < B − V < 0.97. They also have a high signal-to-noise ratio (S/N) from 150 to 450 per pixel, are well fluxed using standard star flux calibrations, and have tight control over instrument resolution and velocity dispersion. Long-slit spectra were obtained using the T2KB chip on the Cassegrain spectrograph on the Kitt Peak Mayall 4 m Telescope (2006 January 31–February 5). A resolution of 1.4 Å was selected to adequately sample the velocity dispersions of the program galaxies, which range from 50 to 350 km s⁻¹. The wavelength range covers from 3200 Å to 7500 Å in two wavelength swaths.

The Graves et al. (2007) sample was constructed from spectra of 22,501 SDSS galaxies that fall into the redshift range 0.06 < z < 0.08 and whose colors meet the criteria (0.11(g − r) > −0.025(0.1 M_r − 5 log h) + 0.42, with h = 0.70 (Yan et al. 2006), placing them firmly within the red sequence. These spectra are then further divided into those with Hα and [O ii] emission lines and those without. Those with emission lines and high [O ii]/Hα ratios were said to be “LINER-like” and those without were classified as “quiescent”. Note that LINER stands for “low-ionization nuclear emission-line region”. The high [O ii]/Hα ratios are defined in Yan et al. (2006) as those with EW([O ii]) > 5EW(Hα) − 7 Å.

Graves et al. (2007) found that the [O ii] EW distribution of their quiescent sample has a standard deviation of σ = 1.56 Å. In part to reduce the impact of outliers, which may contain emission just below the detection threshold, they produced a random subsample of 2000 quiescent galaxies selected to conform to a Gaussian distribution centered on an [O ii] EW of 0 and truncated at ±2σ.[O ii]. They then divided these 2000 galaxies into the following velocity bins: 70 km s⁻¹ < σ < 120 km s⁻¹, 120 km s⁻¹ < σ < 145 km s⁻¹, 145 km s⁻¹ < σ < 165 km s⁻¹, 165 km s⁻¹ < σ < 190 km s⁻¹, 190 km s⁻¹ < σ < 220 km s⁻¹, and 220 km s⁻¹ < σ < 300 km s⁻¹. For uniformity in comparison, each spectrum in every bin was smoothed to mimic an equivalent velocity dispersion of σ = 300 km s⁻¹, the highest velocity dispersion in the sample. Finally, they co-added all of the individual spectra in each bin to produce six composite spectra corresponding to quiescent galaxies with different original dispersions. Along with these spectra, the S/N at each resolution element was computed to produce an error spectrum for each of the six composite spectra. Factors that may contribute to the error estimate are age, individual abundances, and emission signal. The error spectrum is likely to be dominated almost entirely by measurement uncertainty given the poor S/N of the individual SDSS spectra.
We adopt the six composite spectra from Graves et al. (2007) for analysis and comparison with the Virgo spectra. The SDSS data points in the figures of this paper represent indices measured from those composite spectra.

The central aim of this paper is to measure the strength of any residual hydrogen emission in these quiescent spectra. Noting the apparent residual Hα emission of the SDSS spectra as seen in the first panel of Figure 1, we construct simple formulae for the correction of the relative intensities of the rest of the Balmer series for the SDSS as a function of Mg b that includes continuum slope effects and the intrinsic decrement values for the Balmer lines. The corrections should find future use with integrated-light models to better predict stellar population parameters, especially the mean metallicities and ages of galaxies.

Our analysis methods and results are set out in the following section with a discussion and summary in Section 3.

2. ANALYSIS AND RESULTS

For this work, the Hα pseudo-EW index is as defined by Cohen et al. (1998). The first panel of Figure 1 shows that there is a discrepancy in the Hα measurements between the SDSS and Virgo spectra. Plausibly, this is due to either hydrogen emission in the SDSS spectra or non-spectrophotometric wavelength-dependent fluxing errors that would propagate into Lick index measurements depending on how the various passbands lay across the various spectral “lumps.” We infer that the bulk of the discrepancy is most likely due to hydrogen emission in the SDSS spectra because the continuum-shape differences between the data sets is too small to account for much of the discrepancy, as we now show.

To determine if differences in the continuum of the two data sets could explain this discrepancy, the ratio of similar spectra (similar as regards velocity dispersion) from the two data sets was computed and a continuum fit was found for this ratio using the “continuum” routine in IRAF.1 Lick style indices were measured from the fit as one would measure spectra. The delta index thus discovered was found to be small: about 0.05 Å, insufficient to explain the SDSS–Virgo discrepancy. It should be noted that the effects of the continuum differences could be more severe if differences in the continuum shapes exist that are of the same wavelength span as the features of interest. Most would likely lay with the SDSS spectra, since our fluxing of the Virgo data was careful, but unfortunately we do not have the data to check the significance of these differences.

We characterized the SDSS–Virgo Hα–Mg b trend by best-fit lines calculated using fitxy.f (Press et al. 1992). This is a Fortran program for finding the best-fit line for data with errors in both the x and y coordinates. This minimizes the distance of each point from the line while taking into account weighting by the precision of the individual measurements in both the x and y coordinates. The choice to characterize the trends in Hα as a function of Mg b was due to the fact that it is easy to model galaxies of various Mg abundance and measure the strong Mg b feature. Also, since there exists a tight correlation between Mg b and σ, these conclusions can be applied to galaxies of various σ. Those line fits and the root mean square (rms) of the distances of the points from their fit lines are listed in Table 1. Also shown

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Balmer emission fill-in. To determine the form of the correction term, we start with the definition of EW (see Equation (1)). In Equation (1), $\lambda_1$ and $\lambda_2$ are defined as the blue and red wavelength bounds of the index passband, $F_i(\lambda)$ is the flux at each wavelength across the passband, and $F_c$ is the pseudo-continuum flux; see Worthey et al. (1994):

$$\text{EW} = \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{F_i(\lambda)}{F_c} \right) d\lambda = \Delta \lambda \left( 1 - \frac{F_i}{F_c} \right).$$

(1)

With more generality, and including a term for the flux due to an emission feature,

$$\text{EW} = \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{F_i(\lambda) + F_j(\lambda)}{F_c} \right) d\lambda = \Delta \lambda \left( 1 - \frac{F_i}{F_c} - \frac{F_j}{F_c} \right),$$

(2)

where $F_i$ is the flux of the emission feature, $F_j$ is the flux of the stellar light, and $\Delta \lambda = \lambda_2 - \lambda_1$. If we call the emission line’s power $j$, then the average emission line flux is defined by

$$j = \int_{\lambda_1}^{\lambda_2} F_j(\lambda) d\lambda = \Delta \lambda F_j.$$

(3)

Thus, the average stellar flux inside the continuum band is $F_c$ and the correction term for the emission EW is $\Delta \lambda F_j/F_c = j/F_c$. This gives us the equation for the EW of an index with emission as

$$\text{EW} = \Delta \lambda - \Delta \lambda \frac{F_i}{F_c} - \frac{j}{F_c}.$$

(4)

To extend to Balmer lines other than Hα, we exploit the fact that the decrements $j_\beta/j_\alpha$, $j_\gamma/j_\alpha$, and $j_\delta/j_\alpha$ are known, and relatively constant.

For example, if $j_\alpha$ is known, then extending from an Hα index to an Hβ index is accomplished by adding the correction term

$$\frac{j_\beta}{F_{c,\beta}} = \frac{j_\alpha}{F_{c,\alpha}} \times \frac{F_{c,\alpha}}{F_{c,\beta}} \frac{j_\beta}{F_{c,\beta}}.$$

(5)

Having determined the Hα correction from best line fits (see Table 1), all that is left to do is determine the conversion factors $F_{c,\alpha}$ and $j_\alpha$.

To determine $F_{c,\beta}$, a version of the Worthey (1994) and Trager et al. (1998) models was used. These models use a grid of optical synthetic spectra (Lee et al. 2009) in order to investigate the effects of changing the detailed elemental composition on an integrated spectrum. This grid was then used to create synthetic spectra at a variety of ages and metallicities for single-burst stellar populations. The underlying isochrones for this paper were the Worthey (1994) isochrones, because they allow “manual” horizontal branch morphology control.

However, there are certain caveats to using these isochrones. Specifically, the models are a bit crude by today’s standards and the ages are about 2 Gyr too old, so that 17 Gyr should really be interpreted as 15 Gyr. The Bertelli et al. (1994) isochrone sets were used to check the results.

For this paper, new index fitting functions were generated. The data sources include a variant of the original Lick collection of stellar spectra (Worthey et al. 1994) in which the wavelength scale of each observation has been refined via cross-correlation, as well as the MILES spectral library (Sánchez-Blázquez et al. 2006) with some zero-point corrections, and the Coude Feed Library (CFL) of Valdes et al. (2004). The CFL was used as the fiducial set, in the sense that any zero-point shifts between libraries were corrected to agree with the CFL case. The MILES and CFL spectra were smoothed to a common Gaussian smoothing corresponding to 200 km s$^{-1}$. The rectified-Lick spectra were measured and then a linear transformation was applied to put them on the fiducial system.

Multivariate polynomial fitting was done in five overlapping temperature swaths as a function of $\log T_{\text{eff}}$, $\log g$, and [Fe/H]. The fits were combined into a lookup table for final use. As in Worthey (1994), an index was looked up for each “star” in the isochrone and decomposed into “index” and “continuum” fluxes, which added, then reformed into an index representing the final, integrated value after the summation. This gives us empirical synthetic spectra when variations in chemical composition are needed. The grid of synthetic spectra is complete enough to predict nearly arbitrary composition.

These models were then used to determine the continuum level conversion factors. The first step was to take the ratio of the continuum level near Hα with the continuum levels near the other Balmer lines as measured from these models. The next step is to plot these continuum ratios against Mg b. The last step is to fit a least-squares line to these data, giving a prescription for the change of the relative continuum levels as a function of Mg b.

The last piece of the puzzle is that the native relative intensities of the Balmer lines need to be accounted for. This is taken into account by the relative Balmer line intensities as calculated by Osterbrock & Ferland (2006). We adopt case B, 10,000 K conditions, because it is near the middle of the range for star formation regions ($j_\alpha/j_\beta = 2.85$), and it is not too drastically different than LINER-type spectra ($j_\alpha/j_\beta = 3.27$) from Graves et al. (2007). Another reason to use these theoretical decrements is that observed decrements may suffer from asymmetric systematic errors due to local dust. The final correction formulae were applied to the Hβ index defined in Worthey et al. (1994), $H\gamma_A$, $H\gamma_F$, $H\delta_A$, and $H\delta_F$ as defined in Worthey & Ottaviani (1997) and are found in Table 2.

Figures 1 and 2 show the measurements of Virgo and SDSS galaxy averages along with the corrected SDSS data (light blue line). In all the graphs, the Virgo data are in red, while the SDSS data are in green. Also in Figures 1 and 2, model grids are plotted in blue and pink, respectively. The blue corresponds to models of various ages from 1.5 to 17 Gyr and the pink corresponds to models of various metallicities from $-2.00$ to 0.50. For the Hβ correction the line fit is a little low for smaller galaxies with weaker Mg b, but not bad for the larger galaxies (see Figure 1). The most reliable results are obtained for 3.0 Å $< Mg b < 4.3$ Å. This Mg b range covers most elliptical galaxies.

The fits for Hγ and Hδ do not look as good when compared to the Virgo measurements (see Figure 2). The reason for this is most likely the sensitivity of the Hγ and Hδ indices to changes in individual elemental abundances, with perhaps a non-negligible

### Table 1

| Data Set     | Line Fit in Å | rms of Fit in Å |
|--------------|---------------|-----------------|
| Virgo        | 3.0132 − 0.3768 × Mg b | 0.066          |
| SDSS         | 1.3476 − 0.0532 × Mg b | 0.020          |
| Correction term | 1.6656 − 0.3236 × Mg b | $\frac{j_\beta}{F_{c,\beta}}$ | 0.069          |

Notes. Line 3 is the difference between these two best-fit lines, which represents the Hα correction term along with its rms value.
Another reason for choosing Hβ may be to preserve Hα, associating it with the linear offset in Hα as measured in the Virgo galaxies, and suggesting themselves as candidates for contribution from systematic errors between the two data sets. Elements N, C, and O have a profound and interdependent effect on this spectral region, and suggest themselves as candidates for further investigation.

3. DISCUSSION, SUMMARY, AND CONCLUSION

Using the correction factor \( \left( \frac{1}{\delta} \right) \) as derived above and associating it with the linear offset in Hα this work has shown that for SDSS spectra selected and co-added like those in Graves et al. (2007), an emission correction factor on the order of 0.5 Å in Hα and 0.2 Å in Hβ needs to be applied to quiescent galaxies in order to better determine the mean age and metallicity of these composite galaxy spectra. These correction factors are much larger than those estimated in Graves et al. (2007), where the estimated correction factors from measurements of [O ii] give Hα = 0.082 Å and Hβ = 0.027 Å. These new emission corrections, based on derived ages from Graves et al. (2007), would give an estimated 2–3 Gyr older age than those presented. This work also shows that the higher-order Balmer lines Hγ and Hδ have such modest emission corrections that other uncertainties dominate the error budget. At least for our comparison sample of Virgo Cluster elliptical galaxies, Hγ and Hδ suffer from contamination from the varying of other elemental abundances, making age determination from these indices even more complicated. This makes the need for correct Hα and Hβ measurements all the more important, since they are relatively insensitive to changes in metal abundances.

These results are in qualitative agreement with the results from Eisenstein et al. (2003) who showed that in their SDSS spectra Hβ suffers from interstellar emission lines and speculated that non-solar abundance ratios were to blame for the differences in age determinations made from Hβ, Hγ, and Hδ. Not only is there obvious hydrogen emission in the Graves et al. (2007) SDSS spectra, but also it is clear that relative abundance ratios have to be taken into account in order to determine galactic ages from Hγ and Hδ.

For this work, the Hα correction was chosen as the basis for the corrections due to the facts that Hα is \( \sim 3 \) times more sensitive to hydrogen emission than Hβ and that the line fit for Hα as measured in the Virgo galaxies had a much tighter fit (rms = 0.066 Å) compared with Hβ (rms = 0.15 Å). This leads to a corrected SDSS line fit with much less uncertainty, especially for galaxies inside the range 3.0 Å < Mg b < 4.3 Å where the corrections for Hβ yield the most reliable results. Another reason for choosing Hα instead of directly using the correction that one could get from the Hβ plot is that we wanted to preserve Hβ for age determination.

### Table 2

| Balmer Index | Correction Term in Å | Hα Correction in Å \((\frac{\delta F}{\delta \log(\text{age})})\) | Continuum Correction \((\frac{\delta F}{\delta Z})\) | Decrement \((\frac{\delta F}{\delta Z})\) | Correction term \((\frac{\delta F}{\delta Z})\) | Uncertainty in Å |
|--------------|----------------------|------------------------------------------|-----------------|-----------------|-------------------------------|------------------|
| Hβ          | \(\frac{\delta F}{\delta \log(\text{age})} = (1.666 - 0.324(Mg b)) \times (0.838 + 0.076(Mg b)) \times 0.351\) | 0.076          |                  |                  |                               |                  |
| Hγ          | \(\frac{\delta F}{\delta \log(\text{age})} = (1.666 - 0.324(Mg b)) \times (0.847 + 0.149(Mg b)) \times 0.165\) | 0.093          |                  |                  |                               |                  |
| Hδ          | \(\frac{\delta F}{\delta \log(\text{age})} = (1.666 - 0.324(Mg b)) \times (0.649 + 0.293(Mg b)) \times 0.091\) | 0.140          |                  |                  |                               |                  |
| Hβ          | \(\frac{\delta F}{\delta \log(\text{age})} = (1.666 - 0.324(Mg b)) \times (0.649 + 0.293(Mg b)) \times 0.091\) | 0.140          |                  |                  |                               |                  |

Notes. The first error term is that of the Hα correction term found in Table 1. The second is the rms of the continuum correction term fit calculated in the same manner as that of the Hα correction and the third is due to scatter in the possible theoretical values of the decrement.

### Table 3

| Index | Zsp |
|------|-----|
| Hα   | 0.8 |
| Hβ   | 0.8 |
| Hδ (Worthey et al. 1994) | 0.6 |

Notes. Zsp gauges how changes in metallicity and age affect various indices. A large Zsp indicates a larger dependence on the overall metallicity than on the age with 1.0 indicating that age and metallicity affect the index equally.

The plot for Hβ in the second panel of Figure 1 still shows a discrepancy between the corrected SDSS data (light blue line) and the Virgo data (red line). Although, statistically speaking, the discrepancy is of marginal significance, this residual difference could be due to a few variables such as varying abundance ratios within the Virgo galaxies, slightly different decrement values than the ones used here, or the possibility that the Hα emission correction may be in part due to a difference in the mean ages of the two samples. For example, Thomas et al. (2005) showed that cluster galaxies tend to be around 2 Gyr older than field galaxies.

A contributing factor might be that Hα and Hβ have different age sensitivities. In order to investigate the age sensitivities, the Z versus age sensitivity parameter (Zsp) was calculated for both Hα and Hβ as in Worthey et al. (1994). The Zsp parameter is the modeled change in index strength due to a change in fractional metallicity \((Z = 0.01689 \times 10^{(\text{Fe/H})})\) divided by the change in index strength due to a change in fractional population age:

\[
Z_{\text{sp}} = \frac{[\partial I_{\alpha}/(\partial \log(Z))]}{[\partial I_{\alpha}/(\partial \log(\text{age}))]}.
\]

The partial derivative of the index with respect to metallicity is evaluated at age = 12 Gyr, and the partial derivative with respect to age is evaluated at solar metallicity. These sensitivities are shown in Table 3 along with the original Worthey et al. (1994) Hβ sensitivity. Note that the models indicate that both Hα and Hβ are age indicators of the same sensitivity. This implies that the residual difference between the corrected SDSS data and the Virgo data is more likely due to abundance ratios or the decrement values used than it is to the age sensitivities of Hα and Hβ. However, since both Hα and Hβ are insensitive to changes in the abundance ratio variation (Serven et al. 2005)
Figure 2. $H_{\gamma F}$, $H_{\delta A}$, and $H_{\delta F}$ against Mg $b$ indices for two data sets and models. The Virgo spectra (red symbols with error bars), the SDSS composite spectra (green symbols with error bars), single stellar population models (blue grid lines) from bottom to top of ages 17, 12, 8, 5, 3, 2, and 1.5 Gyr, and models from right to left of metallicities 0, 0.25, 0, −0.25, −0.5, −1, −1.5, and −2 (pink grid lines) are plotted. The fits to the index values for the SDSS galaxies from right to left of metallicities 0

and decrement values can change from the effects of local dust, the difference would most likely stem from the choice of decrement. However, the measured extragalactic decrement values tend to be larger than those used here and that using these larger decrements would only increase the observed residual difference! We are therefore forced to postulate that at least one other systematic offset may be operating between the Virgo and SDSS data sets.

The applicability of this work for other samples using composite SDSS spectra may be limited due to the details of the sample selection. It is also unlikely to be applicable to individual red sequence galaxies due to the wide dispersion in index values and possible age effects. One possible avenue could be to scale other averages to match those of Graves et al. (2007), but it would be a better idea to echo the work shown here by comparing with the minimal-emission Virgo data set those averages and determining a new correction.

It is conceptually possible to solve for both age and emission correction by considering both $H\beta$ and $H\alpha$ simultaneously, and increasing the emission correction until both indices give similar ages against a model grid. The obvious trouble with that scheme is that the solution then becomes model-dependent. There is also a strong anticorrelation between derived age and emission correction. There is also the contribution of N emission near $H\alpha$, whose presence may cause spuriously large $H\alpha$ emission measurements in individual galaxies.

Speculation aside, it is safe to say that there is emission contamination in the SDSS spectra and that it is reasonably well accounted for by the linear fits presented in this paper. In data sets that include $H\alpha$, observed O$\text{II}$ and O$\text{III}$ do not need to be used as a proxy for Balmer emission. Emission contamination is much less of a problem for $H\gamma$ used as a proxy for Balmer emission. Emission correction is much less of a problem for $H\gamma$ and $H\delta$, but interpretation of these indices is complicated by the probable effects of individual elemental abundances.

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