STELLAR ABSORPTION LINE ANALYSIS OF LOCAL STAR-FORMING GALAXIES: THE RELATION BETWEEN MASS, METALLICITY, DUST ATTENUATION AND STAR FORMATION RATE

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ABSTRACT

We analyze the optical continuum of star-forming galaxies in SDSS by fitting stacked spectra with stellar population synthesis models to investigate the relation between stellar mass, stellar metallicity, dust attenuation and star formation rate. We fit models calculated with star formation and chemical evolution histories that are derived empirically from multi-epoch observations of the stellar mass—star formation rate and the stellar mass—gas-phase metallicity relations, respectively. We also fit linear combinations of single burst models with a range of metallicities and ages. Star formation and chemical evolution histories are unconstrained for these models. The stellar mass—stellar metallicity relations obtained from the two methods agree with the relation measured from individual supergiant stars in nearby galaxies. These relations are also consistent with the relation obtained from emission line analysis of gas-phase metallicity after accounting for systematic offsets in the gas-phase-metallicity. We measure dust attenuation of the stellar continuum and show that its dependence on stellar mass and star formation rate is consistent with previously reported results derived from nebular emission lines. However, stellar continuum attenuation is smaller than nebular emission line attenuation. The continuum-to-nebular attenuation ratio depends on stellar mass and is smaller in more massive galaxies. Our consistent analysis of stellar continuum and nebular emission lines paves the way for a comprehensive investigation of stellar metallicities of star-forming and quiescent galaxies.

Subject headings: galaxies: evolution — galaxies: ISM — galaxies: formation — galaxies: abundances

1. INTRODUCTION

Measurements of heavy elements and dust provide important constraints for understanding the formation and evolution of star-forming galaxies. Gas from the intergalactic medium flows into dark matter halos fueling star formation in galaxies. Stars are sustained by fusion of lighter elements into heavier elements. These heavy elements are recycled into the interstellar medium (ISM) by stellar mass loss processes. Some fraction of these heavy elements may be expelled from the ISM by galaxy scale outflows. With each generation of star formation, heavy elements and dust—which forms out of heavy elements—accumulate in galaxies. Thus, the heavy element and dust content of galaxies depends on star formation and gas flows. These are key physical processes governing galaxy formation and evolution.

Oxygen is the most abundant heavy element in the universe. The amount of oxygen relative to hydrogen in the gas-phase is an important metric of chemical evolution. The gas-phase metallicity of star-forming galaxies can be measured from strong emission lines observed in rest-frame optical spectra (Searle & Sargent 1972), Lequeux et al. (1979) first showed that gas-phase metallicity of star-forming galaxies scales with stellar mass—the so-called mass—metallicity (MZ) relation. From analysis of ~ 50,000 star-forming galaxies in the Sloan Digital Sky Survey (SDSS), it is now well established that there is a tight MZ relation for galaxies in the local universe (˜ 0.1 dex scatter; Tremonti et al. 2004). The MZ relation is a power-law that flattens or saturates at large stellar masses (Tremonti et al. 2004; Mostekas et al. 2011; Andrews & Martini 2013; Zahid et al. 2013a; Wu et al. 2017).

An MZ relation is observed for star-forming galaxies out to z ∼ 3 (e.g., Savaglio et al. 2005; Erb et al. 2006; Cowie & Barger 2008; Maiolino et al. 2008; Mannucci et al. 2009; Lamareille et al. 2009; Pérez-Montero et al. 2009; Zahid et al. 2011; Yabe et al. 2012; Zahid et al. 2013a, 2014; Wuys et al. 2014; Maier et al. 2015; Salim et al. 2015; Sanders et al. 2015; Ly et al. 2016; Kashino et al. 2017). These observations demonstrate that at a fixed stellar mass, metallicities of galaxies increase with cosmic time. Zahid et al. (2013a) show that the shape and overall normalization of the MZ relation is independent of redshift at z ≤ 2; the evolution of the MZ relation is quantified solely by evolution in the stellar mass where metallicities of galaxies saturate, i.e. the stellar mass where the MZ relation flattens.

The scatter of the MZ relation is correlated with other galaxy properties. A relation between stellar mass, metallicity and SFR is observed in local (SFR Ellison et al. 2008; Mannucci et al. 2010; Lara-López et al. 2010; Yates et al. 2012; Andrews & Martini 2013; Salim et al. 2014) and high-redshift galaxies (Zahid et al. 2014; Yabe et al. 2014; Troncoso et al. 2014; Maier et al. 2015; Salim et al. 2015). At a fixed stellar mass, galaxies with high SFRs tend to have lower metallicities and vice versa.

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Both metallicity and SFR depend on the amount of gas. Thus, the anti-correlation between metallicity and SFR is likely due to variations in gas content (Hughes et al. 2013; Bothwell et al. 2013, 2016).

The shape, evolution and correlated scatter of the MZ relation provide important observational constraints for models of galactic chemical evolution (e.g., Ellison et al. 2008; Finlator & Davé 2008; Mannucci et al. 2010; Davé et al. 2012; Dayal et al. 2013; Lilly et al. 2013; Zahid et al. 2013a, 2014a; Ascasibar et al. 2014; Andrews et al. 2017). Based on these observational constraints and the equations of galactic chemical evolution, Zahid et al. (2014a) develop an analytical model whereby the MZ relation originates from a universal relation between metallicity and stellar-to-gas-mass ratio. In their model, metallicity increases as galaxies build stellar mass but saturates at the point when the mass of metals produced and returned to the ISM by massive stars is equal to the mass of metals forever sequestered within low mass stars.

Stars form from gas composing the ISM and thus a relation between stellar mass and stellar metallicity is expected. Indeed, several studies have reported such a relation between the stellar mass and the metallicity of individual stars and/or the integrated stellar population (Gallazzi et al. 2005; Panter et al. 2008; Kirby et al. 2013; González Delgado et al. 2014; Kudritzki et al. 2016; Bresolin et al. 2016). The stellar MZ relation is qualitatively similar to the gas-phase MZ relation.

The gas-phase metallicity depends on SFR which is likely due to variations in gas content. If these variations occur on sufficiently long timescales, stellar metallicity determined from the integrated stellar population should also depend on SFR. The dependence of the stellar MZ relation on the SFR will be explored in this work.

Dust forms from heavy elements and a correlation between dust and metallicity is observed in the local universe (Heckman et al. 1998; Boissier et al. 2004; Asari et al. 2007; Garn & Best 2010; Xiao et al. 2012; Zahid et al. 2012b) and at high redshifts (Reddy et al. 2010; Zahid et al. 2013). At a fixed stellar mass, dust attenuation measured from the Balmer decrement depends on stellar mass and SFR (Zahid et al. 2013b). At stellar masses below $\lesssim 10^{10} M_\odot$ dust attenuation is anti-correlated with SFR; at stellar masses $\gtrsim 10^{10} M_\odot$ dust attenuation and SFR are positively correlated. Yates et al. (2012) report similar trends for the relation between stellar mass, metallicity and SFR (see also Zahid et al. 2013b). Dust attenuation determined from the continuum is independent of the emission line properties and thus provides an alternative means to investigate the relation between stellar mass, dust attenuation and SFR.

Studies of local galaxies report that nebular lines are more attenuated than the continuum (e.g., Calzetti et al. 1994; Mayya & Prabhu 1996; Charlot & Fall 2000). The canonical ratio of continuum-to-nebular attenuation is 0.44 (Calzetti 1997). However, this ratio may be a function of galaxy properties (e.g., Wuyts et al. 2013; Koyama et al. 2015). We examine the ratio of continuum-to-nebular attenuation as a function of galaxy properties.

The metal and dust content of star-forming galaxies is typically studied via emission line analysis of optical spectra. However, metallicities measured from strong emission lines are subject to large systematic uncertain-

\begin{equation}
\text{log}(\frac{[OIII]\lambda5007}{H\beta}) > \frac{0.61}{\log(\frac{[NII]\lambda6584}{H\alpha}) - 0.05} + 1.3.
\end{equation}

We select galaxies with $H\beta$, $H\alpha$ and $[NII]\lambda6584$ emission lines observed with a signal-to-noise (S/N) ratio $\geq 5$. These selection criteria yield a sample of $\sim 200,000$ star-forming galaxies.

2.2. Stacking Procedure

The techniques we develop in this work can be applied to individual galaxy spectra but the fitting procedure as it is currently implemented is too computationally expensive to apply to large samples. Thus, we stack spectra of galaxies in bins of stellar mass. This approach increases the S/N ratio of the spectra we analyze and requires fewer computations. The stacking procedure is described in detail by Andrews & Martini (2013). Here 1 http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/
Fig. 1.— SDSS spectra of star-forming galaxies stacked in 25 bins of stellar mass ranging from $10^{8.5}M_\odot$ (top) to $10^{11}M_\odot$ (bottom). Stellar mass ranges of stacked spectra are in Table 1.
TABLE 1

<table>
<thead>
<tr>
<th>Stellar Mass Range</th>
<th>( N_S )</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \log(M_\odot/M_\odot) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.50 – 8.60</td>
<td>306</td>
<td>156</td>
</tr>
<tr>
<td>8.60 – 8.70</td>
<td>558</td>
<td>197</td>
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<tr>
<td>8.70 – 8.80</td>
<td>884</td>
<td>247</td>
</tr>
<tr>
<td>8.80 – 8.90</td>
<td>1317</td>
<td>288</td>
</tr>
<tr>
<td>8.90 – 9.00</td>
<td>1898</td>
<td>336</td>
</tr>
<tr>
<td>9.00 – 9.10</td>
<td>2440</td>
<td>413</td>
</tr>
<tr>
<td>9.10 – 9.20</td>
<td>3053</td>
<td>466</td>
</tr>
<tr>
<td>9.20 – 9.30</td>
<td>3931</td>
<td>528</td>
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<td>606</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>10.9 – 11.0</td>
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<td>947</td>
</tr>
</tbody>
</table>

Note. — Columns 1 and 2 give the stellar mass range and number of spectra averaged, \( N_S \), for each stack, respectively. Column 3 lists the median signal-to-noise per pixel between 4400 – 4450\AA.

we highlight the salient aspects of the procedure and refer readers to AM13 for more details.

The data are stacked in 0.1 dex bins of stellar mass with stellar masses ranging between \( 10^{8.5} – 10^{11} M_\odot \). The spectra are corrected for galactic extinction using the maps of Schlegel et al. (1998). The spectra are shifted to rest-frame wavelengths using the measured redshift and linearly interpolated between 3700 – 7360\AA with a wavelength pixel resolution \( \Delta \lambda = 1\AA \). The spectra are normalized to the mean flux between 4400 – 4450\AA and are coadded by taking the mean flux of all spectra in the stellar mass bin at each wavelength pixel element. Each spectrum is equally weighted in the average. To examine galaxy properties as a function of stellar mass and SFR, we sort spectra in each stellar mass bin into quintiles of SFR. Systematics related to the stacking procedure are discussed in AM13.

Figure 1 shows a montage of the 25 stacked spectra analyzed in this study. The number of spectra in each stack and typical S/N ratio are given in Table 1. We empirically determine the spectral resolution of each stacked spectrum from fitting strong emission lines and find that it increases with stellar mass. To avoid systematic effects caused by different spectral resolution, we convolve all spectra such that emission lines have the line width of the most massive galaxy stacked spectrum which is 330 km s\(^{-1}\) (full width at half maximum).

3. METHODS

Our goal is to develop a robust technique to analyze the continuum of star-forming galaxies. We compare stellar metallicities determined from continuum analysis with those derived from standard techniques using ISM emission lines. We derive stellar metallicities by fitting stellar population synthesis models using two independent approaches. We empirically derive star formation and chemical evolution histories and use these as inputs to generate stellar population synthesis models which we fit to data. We also fit the data with a linear combination of models with single bursts of star formation which we sample at different metallicities and ages.

Fitting stellar population synthesis models with prescribed histories has the advantage that the results can be easily interpreted when the inputted star formation and chemical evolution histories appropriately characterize the data. This is the case when we fit spectra averaged in bins of stellar mass. However, these models cannot be applied in general. When we sort stacked spectra of star-forming galaxies into quintiles of SFR, the average star formation and chemical evolution histories we use as model inputs are no longer valid and thus those models are inapplicable. The single burst model fitting procedure makes no assumptions about the star formation and chemical evolution history. Thus, we demonstrate the consistence of the two approaches for data stacked only in bins of stellar mass. We then apply the single burst models to the stacked spectra sorted in quintiles of SFR.

3.1. Gas-Phase Oxygen Abundance

The spectra in Figure 1 show strong emission lines from ionized gas in star-forming regions. We measure the gas-phase oxygen abundance using line flux ratios corrected for dust attenuation. We correct emission line fluxes using the Cardelli et al. (1989) extinction law assuming case B recombination value for the H\(\alpha/H\beta \) emission line ratio of 2.86 (Hummer & Storey 1987). We determine the gas-phase oxygen abundance using the strong-line calibration of Kobulnicky & Kewley (2004, KK04 hereafter). The relevant emission line ratios are

\[
R23 = \frac{[OII]\lambda3727 + [OIII]\lambda4959 + [OIII]\lambda5007}{H\beta} \tag{2}
\]

and

\[
O32 = \frac{[OIII]\lambda4959 + [OIII]\lambda5007}{[OII]\lambda3727}. \tag{3}
\]

We assume that the \([OIII]\lambda5007 \) to \([OIII]\lambda4959 \) emission line ratio is 3:1 (Osterbrock 1989) and adopt 1.33 times \([OIII]\lambda5007 \) line flux when summing the two lines. The \( R23 \) line ratio has two metallicity branches and we use the \([NII]/H\alpha \) ratio to determine the branch. Only a small fraction (< 1%) of galaxies are on the lower metallicity branch.

Metallicity diagnostics using strong emission lines are empirically and/or theoretically calibrated (for review see Kewley & Ellison 2008). Kewley & Ellison (2008) show that different diagnostics applied to the same galaxies yield inconsistent measurements of metallicity. In particular, the absolute calibration varies by \( \gtrsim 0.4 \) dex. However, by comparing several diagnostics, they conclude that most calibrations are accurate in a relative sense. Thus, while the zero-point of the relation between stellar mass and gas-phase oxygen abundance is uncertain, the shape of the relation is more robust.
3.2. Stellar Population Synthesis Modeling and Fitting

In addition to nebular emission lines, spectra in Figure 1 show absorption lines in the continuum emitted by the integrated stellar population. These absorption lines encode information about stellar metallicity. Kudritzki et al. (2016) (and references therein) demonstrate that stellar absorption line spectroscopy is an accurate tool to determine metallicity of individual blue supergiant stars in nearby galaxies. Here we apply a similar spectral fitting technique except we use model spectra calculated with a stellar population synthesis approach rather than model spectra of individual stars.

Strong ISM emission and absorption lines as well as strong stellar Balmer lines contain the stacked stellar metal line spectra at certain wavelengths. When fitting stacked spectra with models, we avoid the near ultraviolet part of the spectrum which is dominated by a series of absorption lines (Calcium H,K and Balmer series) and the [OII]λ3727 emission line and limit our analysis to the spectral range of 4140 − 7300Å. In this range we mask out a 30Å region centered on each ISM absorption and emission line. However, for the Balmer lines we mask out 75Å region to exclude the pressure broadened line profile wings. These masking windows are appropriate for the spectral resolution of the data.

We calculate model spectra using the Flexible Stellar Population Synthesis (FSPS; v3.0) code (Conroy et al. 2009; Conroy & Gunn 2010). We adopt the Chabrier (2003) initial mass function, the Medium-resolution Isaac Newton Telescope Library of Empirical Spectra (MILES) library (Sánchez-Blázquez et al. 2006) and the Mesa Isochrones and Stellar Tracks (MIST; Dotter 2016; Choi et al. 2016). The intrinsic resolution of the model spectra is 2.5Å (Falcón-Barroso et al. 2011; Beifiori et al. 2011) which we convolve to match the resolution of the stacked spectra (i.e. 330 km s^{-1}).

3.2.1. Metallicity from Look Back Models

We calculate “look back” models by inputting empirically constrained star formation and chemical evolution histories. Star formation history is not a free parameter, thus we do not need the observed shape of the spectrum of the integrated stellar population as a constraint for the analysis. We normalize stacked and model spectra by fitting a polynomial of degree 20. We divide the spectrum of the integrated stellar population as a constraint for the analysis. We infer these histories using the evolutionary model presented in Zahid et al. 2012b (see also e.g., Conroy & Wechsler 2009; Peng et al. 2010; Papovich et al. 2011; Leitner 2012). We use these histories as inputs to the FSPS code to generate model spectra. We refer to these as the look back stellar population synthesis (LBSPS) models. The basic assumption of these models is that galaxies evolve along the average measured relations between stellar mass and SFR and stellar mass and gas-phase oxygen abundance.

We adopt the parameterization given in Behroozi et al. (2013, parameters in Table 8) for the star formation rate measurements as a function of stellar mass and redshift. This parameterization is based on a large compilation of published values from the literature spanning a broad redshift range (0 < z < 8). Z14 consistently measure the MZ relation for galaxies out to z ∼ 1.6. We adopt the relation they derive (Equations 6 - 8 in Z14).

Figures 2A and 2B show the stellar mass and star formation rate as a function of cosmic time for three example model galaxies. We assume that stellar mass is instantaneously returned to the ISM and adopt a return fraction of 0.43 (Vincenzo et al. 2016). We evolve models to z ∼ 0.08, the median redshift of the sample. The stellar mass estimates used in Z14 and Zahid et al. (2012a) are 0.25 dex smaller than stellar masses used in this study. We add 0.25 dex to stellar masses and SFRs outputted by the evolutionary model.

We use observations of the MZ relation as a function of redshift to infer the chemical evolution histories of model galaxies. Z14 parameterize the relation as

$$12 + \log(O/H) = Z_0 + \log \left(1 - \exp \left(-\frac{M_*}{M_{\odot}}\right)\right).$$

In this model, $Z_0$ is the saturation metallicity quantifying the asymptotic metallicity limit (Moustakas et al. 2011; Zahid et al. 2013b). $M_{\odot}$ is the characteristic turnover mass where the MZ relation begins to saturate and $\gamma$ is the power-law slope of the relation at $M_\ast < M_{\odot}$. Z14 show that $Z_0$ and $\gamma$ do not evolve significantly at $z < 1.6$ and the redshift evolution of the MZ relation is quantified by evolution of $M_{\odot}$ which goes as $\propto (1 + z)^{0.64}$. Given the uncertainty in the absolute metallicity calibration, in Figure 2C we renormalize $Z_0$, i.e. the saturation metallicity, to the value measured by AM13 using the direct method metallicity determination. Figure 2C shows the metallicity history of three example model galaxies.

We use $Z_0$ in Equation 4 as a free parameter when calculating the chemical evolution history for our evolutionary models. We do this for two reasons. First, the zero-point of the gas-phase abundance scale is uncertain (Kewley & Ellison 2008). Second, we want to determine the metallicity of the stellar population and, thus, we need a grid of models with a range of metallicities. For each stellar mass bin we generate a set of LBSPS models. Each set has metallicity offsets to $Z_0$ by a constant factor $\Delta Z_0$ such that $-0.75 \leq \Delta Z_0 \leq 0.75$ evenly spaced by 0.05 dex. An example is shown in Figure 3. The chemical evolution histories shown all evolve according to the Z14 relation, but the different color curves correspond to 0.05 dex offsets in $Z_0$ of Equation 4.

Our approach yields model spectra with different final metallicities for each stellar mass bin. Figure 3B shows an example of model spectra in a small spectral window along with the stacked spectrum of galaxies with $10^{10} M_\odot < M_\ast < 10^{10.1} M_\odot$. The flux variation in the LBSPS models is due solely to metallicity; the star formation history for the models are identical. We determine the best-fit metallicity by minimizing the residuals between the various models and the observed stacked spectrum. Figure 3C shows the root-mean-square (RMS) difference between the observed spectrum and the models. The RMS shows a clear minimum as a function of metallicity. Here the metallicity being plotted is the final metallicity of the LBSPS model. The stacked spectrum at all stellar masses have well defined minima in the RMS similar to Figure 3C.
Fig. 2.— (A) Stellar mass and (B) star formation history of galaxies that evolve along the mean relation between stellar mass and SFR observed at several epochs. (C) Metallicity history of the same model galaxies assuming they evolve along the mean MZ relation measured at several epochs. The dashed, dotted and solid curves are examples of three model galaxies with stellar masses of $\sim 10^{9.5}$, $10^{10.25}$ and $10^{11}M_\odot$ at $z \sim 0$. The stellar mass and metallicity histories derived from these models are used as inputs to generate FSPS model spectra.

Fig. 3.— Example of an FSPS look back model spectrum fit. (A) Chemical evolution history for evolution models with different offsets $\Delta Z_0$ of the zero-point $Z_0$ in Equation 4. Offsets range between $-0.75 < \Delta Z_0 < 0.75$ (for details, see text). (B) Example of model template spectra in one narrow spectral window calculated using FSPS and tabulated star formation and metallicity history based on the models shown in Figure 2. Colors correspond to (A). The dashed line is the observed stacked spectrum for galaxies with $10^{10} \leq M_*/M_\odot \leq 10^{11}$. (C) RMS difference between the stacked spectrum and model spectra plotted as a function of final metallicity. The best-fit metallicity is determined by fitting a parabola to points around the minimum RMS. The best-fit metallicity represents the final metallicity of a galaxy evolving along the MZ relation and is interpreted as the metallicity of the young stellar population.

Figure 4 shows the stacked spectrum over the full wavelength range analyzed along with the best-fit model. The data are well fit across the full wavelength range.

We fit stacked data at each stellar mass following the procedure outlined in Figure 3. The RMS of the best-fit ranges between $3 - 6 \times 10^{-3}$. We quote the final metallicity of the LBSPS model as the metallicity measurement. We interpret this metallicity as the metallicity of the young stellar population.

We estimate the systematic uncertainty in metallicity is $\sim 0.1$ dex. The major sources of uncertainty are the absolute calibrations of stellar masses and SFRs. We vary these quantities by 0.25 dex and generate new LBSPS models. We find that metallicities vary systematically by $\sim 0.1$ dex; the shape of the MZ relation is robust.

3.2.2. Metallicity and Dust Attenuation from Sequential Single-Burst Models

Metallicities determined from fitting the LBSPS models provide a fiducial measurement. However, these models assume star formation and chemical evolution histories. Therefore, as an alternative approach, we also fit data with models calculated from a linear combination of sequential single burst (SSB) model spectra. These models are sampled at a range of metallicities and ages. Unlike LBSPS model fits, the star formation history and ages of galaxies are free parameters in this approach. We generate a grid of 216 single burst models sampled at 12 metallicities ranging between $-2.5 \leq \log(Z/Z_\odot) \leq 0.5$ spaced at the intrinsic sampling of the MIST isochrones and 18 stellar population ages logarithmically spaced be-
Fig. 4.— (A) The black curve shows the stacked spectrum for galaxies with $10^{10} < M_*/M_\odot < 10^{10.1}$ and the red curve is the best-fit LBSPS model. Both spectra are normalized to unity across the full wavelength range by a high-degree polynomial fit (see text for detail). (B) Residuals of the fit in (A).

Fig. 5.— (A) The black curve shows the stacked spectrum for galaxies with $10^{10} < M_*/M_\odot < 10^{10.1}$ and the red curve is the best-fit SSB model. Both spectra are normalized to the average flux between 4400–4450 Å. (B) Residuals of the fit in (A).

The shape of the stellar continuum is set by the star formation history and dust attenuation. The star formation history constrains the relative contribution of stars at different stellar masses and dust preferentially absorbs blue light making galaxies appear redder. To use this information when applying the SSB model fits, we use the shape of the continuum to additionally dust attenuation. This is different from the LBPS approach described in the previous section. The relative flux of the model spectrum as a function of wavelength in this case is not normalized by fitting a high degree polynomial. The relative model flux is calculated as

$$M_\lambda = \frac{1}{C_\lambda(A_V)} \sum_{i} b_if_{\lambda,i}. \quad (5)$$

Here, the sum is over all single burst models $f_{\lambda,i}$ scaled by $b_i$ and $C_\lambda$ is the attenuation correction to the flux which we parameterize by the visual attenuation, $A_V$. We adopt the Cardelli et al. (1989) extinction law and a corresponding selective extinction ratio of $R_V = 3.1$ to determine $C_\lambda$. The free parameters of the model are $A_V$ and $b_i$. We determine the best-fit by minimizing residuals using the MPFIT set of routines in IDL (Markwardt 2009).

Each single burst model $f_{\lambda,i}$ is sampled at a metallicity $Z_i$. We derive metallicity for each stacked spectrum from the best-fit parameters

$$Z(M_*) = \sum_{i} b_i\log(Z_i). \quad (6)$$

Here, $Z$ is the derived metallicity.

SSB model fits also constrain ages of the stellar populations. However, we have optimized our approach to determine metallicity and thus have masked out strong Balmer absorption lines. These absorption lines are age sensitive features of the continuum but in star-forming galaxies, they are contaminated in their age sensitive line cores by strong ISM emission lines. We find our procedure is not sensitive to stellar population age and thus we do not report the age here.

Figure 5 shows the fit of SSB models to a stacked spectrum. The RMS of all fits ranges between $5 - 10 \times 10^{-3}$; about twice the value of the LBPS fits. The larger RMS is due to the greater difference between the stacked data and models at wavelengths $> 6500$ Å.

The metallicity we derive by fitting stacked data with SSB models represent an average global property of the stellar population. To assist in our interpretation of metallicities derived from Equations 6, we fit the LBSPS models with our SSB fitting procedure. We fit the LBSPS models with stellar masses $10^{8.5} \leq M_*/M_\odot \leq 10^{11}$ and $\Delta Z_0 = 0$. We fit LBSPS model spectra with SSB spectra because the metallicity of the LBSPS model stellar population is known. Thus, we can compare the metallicity derived from the SSB fit with known quantities to understand what stellar population metallicity we
are sensitive to with our SSB fitting procedure.

Figure 6 shows the metallicity of the LBSPS stellar population compared to the metallicity derived from the SSB model fits. The green curve shows the inputted metallicity for the most recently formed stellar population contributing to the model spectra. Thus, the green curve is the metallicity of the young stellar population. The blue dashed and red dotted curves are the $V$-band luminosity- and mass-weighted stellar metallicities calculated from the star formation and chemical evolution histories used to generate the LBSPS models. The black curve is the metallicity determined by fitting SSB models to the LBSPS models. The SSB fit metallicity is most consistent with the luminosity-weighted metallicity. By comparing the SSB fit results with the luminosity-weighted metallicity in Figure 6, we estimate that the metallicity derived from the SSB fit systematically varies from the luminosity-weighted quantity by $\lesssim 0.04$ dex.

4. THE MASS-METALLICITY RELATION

We examine the relation between stellar mass and metallicity by applying the three methods outlined in the previous section. We determine metallicities from emission lines and absorption lines. We generically refer to the relation between metallicity and stellar mass as the MZ relation. We critically compare MZ relations...
obtained with the three methods.

We start by analyzing the strong ISM emission lines. We measure metallicity for each galaxy in the sample using the method described in Section 3.1. The gas-phase MZ relation is shown in Figure 7A. The red curve is a fit of the observed MZ relation with the model given in Equation 4. The gray dashed curve shows the MZ relation determined by Z14 using a different sample selection criteria. The consistency of the two relations demonstrates that the gas-phase MZ relation is robust to the selection criteria. The best-fit parameters are provided in Table 2.

Next we use LBSPS models to fit the stellar metal absorption lines in the stacked spectra using the method described in section 3.2.1. Figure 7B shows the corresponding MZ relation. We fit the MZ relation with the model given in Equation 4. The best-fit is shown and the parameters are in Table 2.

Finally we use SSB models to fit stellar metal absorption lines in stacked spectra using the method described in section 3.2.2. Figure 7C shows the corresponding MZ relation. The blue curve is a fit to the MZ relation parameterized by Equation 4. The fit parameters are in Table 2.

Figure 7D shows a comparison of the MZ relations determined from the three methods. The gas-phase MZ relation is reasonably consistent with the MZ relation from fitting LBSPS models when it is shifted by -0.33 dex. This shift corresponds to the difference in the $Z_0$ we measure using the two approaches. The LBSPS model results also correspond to the metallicity of the young stellar population. Such a shift is within the range of absolute calibration uncertainties of the strong ISM emission line diagnostics (Kewley & Ellison 2008). For reference, the MZ relation derived using the direct method is similarly offset by $\sim$0.3 dex from the MZ relation derived using the KK04 calibration (AM13). Thus, the LBSPS relation is consistent within a few tenths of a dex with the direct method gas-phase MZ relation.

The MZ relation derived from the two methods using stellar metal absorption lines are in reasonable agreement, though there is an offset that scales with stellar mass. Metallicity derived using the LBSPS model fit represents the metallicity of the young stellar population whereas metallicity determined from fitting SSB models is closer to a luminosity-weighted average. Metallicity increases as galaxies evolve and thus we expect luminosity weighted metallicities to be smaller than the metallicity of the young stellar population. We see this in Figure 6A. The difference between the LBSPS and SSB MZ relations is qualitatively consistent with this conclusion.

Table 2: MZ Relation Fit

<table>
<thead>
<tr>
<th>Sample</th>
<th>$[Z_0/Z_{\odot}]$</th>
<th>log$(M_*/M_{\odot})$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-Phase (Z14)</td>
<td>0.412±0.002</td>
<td>9.469±0.007</td>
<td>0.513±0.009</td>
</tr>
<tr>
<td>Gas-phase</td>
<td>0.419±0.001</td>
<td>9.486±0.003</td>
<td>0.525±0.003</td>
</tr>
<tr>
<td>LBSPS</td>
<td>0.084±0.019</td>
<td>9.63±0.08</td>
<td>0.51±0.03</td>
</tr>
<tr>
<td>SSB</td>
<td>0.075±0.020</td>
<td>9.79±0.08</td>
<td>0.56±0.03</td>
</tr>
</tbody>
</table>

We constrain dust attenuation of the stellar population when fitting SSB models. Figure 8A displays the relation between dust attenuation and stellar mass. The continuum attenuation is measured from fitting the stacked spectra with SSB models. Nebular emission attenuation is measured from the Balmer decrement (see also, Brinchmann et al. 2004; Stasińska et al. 2004; Asari et al. 2007; Garn & Best 2010; Zahid et al. 2013b). Both measurements show similar trends; massive galaxies are more attenuated.

Figure 8B shows the continuum-to-nebular attenuation ratio. Nebular emission is more attenuated than the continuum and the difference scales with stellar mass; massive galaxies exhibit higher levels of nebular attenuation relative to the continuum.

Calzetti et al. (1994) find that attenuation determined from the Balmer line ratio is a factor of $\sim$2 larger than attenuation determined from the UV continuum. They suggest that this is due to an inhomogeneous dust distribution. Young, massive stars are typically found in dustier regions than the underlying stellar population. The canonical ratio of continuum-to-nebular attenuation is 0.44 (Calzetti 1997). However, studies suggest that this ratio may be a function of galaxy properties (e.g., Wuyts et al. 2013; Koyama et al. 2015). Based on ultraviolet-to-infrared observations, Koyama et al. (2015) find that for most of their sample the ratio varies between 0.44 and 1 and the ratio tends to be smaller for the most massive galaxies. Results in Figure 8 are consistent with this type of variation in the ratio. Our results only pertain to the central regions of galaxies covered by the SDSS fiber. However, the consistency with Koyama et al. (2015) suggest our results may be indicative of global galaxy properties.

6. STELLAR MASS, METALLICITY, DUST EXTINCTION AND STAR FORMATION RATE

We examine the relation between stellar mass, metallicity, dust attenuation and SFR by analyzing stacked spectra sorted into quintiles of SFR. We fit stacked stellar absorption line spectra with SSB models to determine metallicity and dust attenuation. Figure 9A shows the median SFRs of the stacked data.

Figure 9B shows the MZ relation for galaxies as a func-
Fig. 9.— (A) Median SFR corresponding to stacked spectra sorted in quintiles of SFR. (B) MZ relation and (C) stellar mass - dust attenuation relation as a function of stellar mass and SFR determined from fitting SSB models. The colored curves in (B) and (C) correspond to SFRs shown in (A).

tion of SFR. At the lowest stellar masses, the data are noisy. At intermediate stellar masses, there appears to be a weak anti-correlation between metallicity and SFR; galaxies with high SFRs have lower metallicities and vice versa. Similar trends between metallicity and SFR are reported for galaxies when metallicities are determined using strong emission lines (Mannucci et al. 2010; Lara-López et al. 2010; Yates et al. 2012).

Figure 9C shows the relation between stellar mass, SFR and dust attenuation. At lower stellar masses (< 10^{10.2} M_\odot), dust attenuation is anti-correlated with SFR; similar to the anti-correlation between metallicity and SFR. There is a sharp transition in the relation at M_* \sim 10^{10.2} M_\odot and the trend reverses at higher stellar masses such that there is a positive correlation between dust attenuation and SFR.

The trend in dust attenuation shown in Figure 9C is remarkably consistent with reported trends between stellar mass, dust attenuation and SFR based on emission line analysis (Zahid et al. 2013b). We reproduce the emission line analysis result in Figure 10 using our sample of SDSS galaxies.

Zahid et al. (2013a) develop a model of dust efflux which reproduces the observed trends between stellar mass, dust attenuation and SFR. In their model, dust content is set by the difference in the rate of dust production and loss. A key aspect of their model is that at a fixed stellar mass, galaxies with large (small) SFRs are younger (older) and thus the difference between dust efflux and dust production lead to the opposite dependence of dust attenuation on SFR at low stellar masses as compared to high stellar masses. Dust attenuation measured from stellar continuum analysis presented in this work provides independent confirmation of the results presented in Zahid et al. (2013b) and Zahid et al. (2013a).

7. DISCUSSION

The gas-phase MZ relation based on emission line analysis of star-forming galaxies in the SDSS has been extensively studied (e.g., Tremonti et al. 2004; Kewley & Ellison 2008; Yates et al. 2012; Andrews & Martini 2013). We critically compare the MZ relation derived from stellar continuum absorption line analysis with the gas-phase MZ relation. We find that after accounting for absolute uncertainties in the zero-point of the gas-phase metallicity calibration, the MZ relation measured from the stellar continuum is consistent with the relation derived from emission lines. The stellar metallicities we derive are completely independent of the emission line analysis and thus the consistency in the stellar and nebular MZ relations for star-forming galaxies is an important confirmation of previously reported results.

The shape of the MZ relation provides important constraints for understanding the chemical evolution of galaxies. Z14 posit that the MZ relation originates from
a more fundamental relation between metallicity and stellar-to-gas-mass ratio. Their inflow model (see Equation 4 and Larson 1972) suggests that chemical evolution is characterized by three distinct regimes: gas-rich, gas-poor and gas-depleted.

Less massive galaxies tend to be gas-rich and their metallicity is proportional to the stellar-to-gas-mass ratio. Thus, the Z14 model predicts that the power-law slope of the MZ relation (γ in Equation 4) should be set by the slope of the relation between gas mass and stellar mass. Based on the measured slope of the stellar-to-gas-mass relation (e.g., Peeples et al. 2014), the MZ relation slope should be γ ∼ 0.5 which is consistent with our measurements (see Table 2).

In the gas-poor regime, the stellar mass exceeds the gas mass. The metallicity increases as gas is consumed and a progressively larger fraction of the ISM metals become locked up in low mass stars; the MZ relation begins to saturate. In the gas-depleted regime, metallicity can become large because the gas content is small and thus does not dilute the metal reservoir. At some point, the mass of metals produced by massive stars equals the mass of metals locked up in low mass stars. The metallicity can not increase beyond this level and the MZ relation saturates. The saturation of the stellar mass-stellar metallicity relation should occur at larger stellar masses as compared to the gas-phase MZ relation. This is because the gas-phase abundances are an instantaneous measure of the metallicity whereas stellar metallicities are an integrated property. Saturation occurs only when a large enough fraction of stars form in the saturation regime. We find that stellar MZ relation saturates at a stellar mass that is 0.2 − 0.3 dex larger than the gas-phase MZ relation.

Several studies report a dependence of the MZ relation on SFR (Mannucci et al. 2010; Lara-López et al. 2010; Yates et al. 2012; Bothwell et al. 2013; Salim et al. 2014). At stellar masses below the saturation metallicity, all these studies report an anti-correlation between metallicity and SFR. A straightforward interpretation of this dependence is that higher gas fractions dilute the metal reservoir, lowering the metallicity. Higher gas fractions also support larger SFRs, thus the anti-correlation between metallicity and SFR. A similar, albeit weaker, anti-correlation exists between stellar metallicity and SFR at a fixed stellar mass (see Figure 9A).

Variations in gas content appear to drive the correlation between metallicity and SFR at a fixed stellar mass. Gas content variations probably result from variations in the accretion history of galaxies (Dutton et al. 2010). The timescale of the deviation of galaxy gas content from the population average must be sufficiently long such that scatter in the MZ relation which is correlated with SFR can be measured in integrated light. Detailed chemical evolution modeling which is beyond the scope of this work may provide constraints for this timescale.

Figure 11 shows a comparison of stellar metallicities we measure with results published in the literature. The MZ relation we derive is consistent with the relation derived by Kudritzki et al. (2016) based on analysis of individual supergiant stars. With the inclusion of the Kirby et al. (2013) results, the relation appears to be continuous over > 7 orders of magnitude in stellar mass. The Gallazzi et al. (2005) MZ relation is qualitatively similar to our results but differs quantitively. The Gallazzi et al. (2005) relation is measured from Lick indices and they combine the star-forming and quiescent galaxy populations. Thus, differences may be due to systematics in the measurement technique and/or sample selection.

8. CONCLUSION

We analyze stellar absorption line continua of star-forming galaxies in SDSS to determine the relation between stellar mass, metallicity, dust attenuation and star formation rate. We stack spectra of star-forming galaxies in bins of stellar mass and fit the data with stellar population synthesis models. The continua of star-forming galaxies are remarkably consistent with model spectra calculated using empirically determined star formation and chemical evolution histories.

We also fit the data with a linear combination of single burst models sampled at a range of metallicities and ages. The star formation and chemical evolution histories of these models are not constrained. This approach yields metallicities consistent with those determined from fitting the empirically constrained models. We conclude that for star-forming galaxies the relation between stellar mass and stellar metallicity is consistent with the relation between stellar mass and gas-phase metallicity once we account for systematic uncertainties in the absolute calibration of the gas-phase metallicity. This consistency is expected from simple models of galactic chemical evolution.

We analyze the stellar metallicity and continuum dust
attenuation of galaxies as a function of their star formation rate. Our results based on analyzing the continuum are consistent with previously reported trends based on emission line analysis, thus providing an independent confirmation of those results. At a fixed stellar mass, the metallicity is anti-correlated with star formation rate which is consistent with the results of e.g., Mancucci et al. (2010) and is expected if there is a universal relation between metallicity and stellar-to-gas mass ratio as suggested by Zahid et al. (2014b). The dependence of the dust attenuation of the continuum on star formation rate is also consistent with analysis based on the Balmer decrement (Zahid et al. 2013b).

Our analysis provides a framework for understanding the relation between gas-phase and stellar metallicities of star-forming galaxies. The results pave the way for future efforts jointly analyzing the star-forming and quiescent galaxy population. A consistent set of models and methods applied to star-forming and quiescent galaxies allows for an exploration of the means by which star-forming galaxies deplete their gas supply eventually shutting down star formation. A comprehensive study of the gas-phase and stellar metallicities of star-forming galaxies and the stellar metallicities of quiescent galaxies (see e.g., Conroy et al. 2014) is already possible. The SDSS provides a wealth of spectroscopic data and the results of e.g., Conroy et al. (2014) is already possible. The SDSS-III collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

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