A Comparison of Stellar and Gas-Phase Chemical Abundances in Dusty Early-Type Galaxies

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ABSTRACT
While we observe a large amount of cold interstellar gas and dust in a subset of the early-type galaxy (ETG) population, the source of this material remains unclear. The two main, competing scenarios are external accretion of lower mass, gas-rich dwarfs and internal production from stellar mass loss and/or cooling from the hot interstellar medium (ISM). We test these hypotheses with measurements of the stellar and nebular metallicities of three ETGs (NGC 2768, NGC 3245, and NGC 4694) from new long-slit, high signal-to-noise ratio spectroscopy from the Multi-Object Double Spectrographs (MODs) on the Large Binocular Telescope (LBT). These ETGs have modest star formation rates and minimal evidence of nuclear activity. We model the stellar continuum to derive chemical abundances and measure gas-phase abundances with standard nebular diagnostics. We find that the stellar and gas-phase abundances are very similar, which supports internal production and is very inconsistent with the accretion of smaller, lower metallicity dwarfs. All three of these galaxies are also consistent with an extrapolation of the mass-metallicity relation to higher mass galaxies with lower specific star formation rates. The emission line flux ratios along the long-slit, as well as global line ratios clearly indicate that photoionization dominates and ionization by alternate sources including AGN activity, shocks, cosmic rays, dissipative magnetohydrodynamic waves, and single degenerate Type Ia supernovae progenitors do not significantly affect the line ratios.

Key words: galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: general – galaxies:ISM – galaxies: stellar content

1 INTRODUCTION
One simplistic way to distinguish late and early-type galaxies is by their dust content and star formation. While late-type galaxies contain large amounts of dust and have on going star formation, early-type galaxies (ETGs) were thought to lack cold interstellar material and have lower star formation rates. However, infrared observations of ETGs starting in the late 1980s revealed cold, interstellar dust in a substantial subset of the population (Jura et al. 1987; Knapp et al. 1989; Goudfrooij & de Jong 1995; Bregman et al. 1998). Subsequent studies of ETGs with archival Hubble Space Telescope (HST) and Spitzer images show that approximately 60% contain a substantial amount of interstellar dust on the order of $10^6 M_\odot$ (Smith et al. 2012; Martini et al. 2013). Though the source of this dust was unclear, the two most common scenarios are external accretion through interactions with low metallicity dwarf galaxies and internal production by evolved star mass loss and/or gas cooling from the hot phase of the interstellar medium (ISM).

Mass loss from evolved stars could explain the 10-12 \(\mu\)m dust signatures seen in many elliptical galaxies (Knapp et al. 1992), but the viability of internal production requires an equilibrium between dust production and destruction to sustain the observed dust masses. Thermal sputtering in the hot ISM (Draine & Salpeter 1979) should destroy dust on a timescale of $t_{\text{dust}} \approx 2 \times 10^{4-7}$ yr (Goudfrooij & de Jong 1995; Clemens et al. 2010; Smith et al. 2012). Given this destruction time and assuming that stars eject material at a constant rate, Martini et al. (2013) derived an internally produced, steady-state dust mass of $10 - 100(t_{\text{dust}}/2 \times 10^4 \text{yr}) M_\odot$-orders of magnitude lower than the $10^{5-6.5} M_\odot$ of dust detected in about half of the population. Similar work by Rowlands et al. (2012) and Smith et al. (2012) conclude that dust destruction timescales would need to be much larger in order to produce the observed dust masses.

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The inclusion of cooling from the hot phase of the ISM in dust lifetime models could explain the observed dust properties. Assuming characteristic Milky Way dust lifetimes (10$^7 – 10^8$ yr) and stellar mass loss rates suggested by mid-infrared ETG emission (0.1–1 M$_\odot$ yr$^{-1}$), mass loss from AGB stars could produce gas reservoirs of 5 x 10$^5$ to 5 x 10$^7$ M$_\odot$ (Athey et al. 2002). After entering the hot ISM, these reservoirs of dusty gas could cool through thermal collisions (Mathews & Brightenberg 2003). The dust would then clump and collect into clouds, shielding the material and producing the observed emission.

With the addition of cooling, internal dust production becomes a plausible dust source. However, it does not explain the lack of dust in some ETGs. Given ETGs’ similar evolution and stellar properties, we expect consistent dust masses across similar populations. Instead, only about 50-60% of ETGs contain measurable amounts of dust (Tran et al. 2001; Smith et al. 2012; Martini et al. 2013). The remainder show no evidence for interstellar dust. The bifurcation between dusty and dustless galaxies, rather than a continuum of dust masses, is inconsistent with internal production. These demographics suggest that stellar mass loss and gas cooling cannot be the only source of interstellar dust in ETGs, or that there is some other important deviation from their apparent self-similarity.

Alternatively, external accretion of dwarf galaxies could explain the surplus of dust in a subset of the population. HST images reveal that many ETGs contain chaotic and clumpy dust lanes–morphology suggestive of past merger events (van Dokkum & Franx 1995). There is also significant kinematic evidence for a rich merger history from alignments between the molecular gas and the stellar populations, most recently from ATLAS3D (Bertola et al. 1992; Morganti et al. 2006; Young et al. 2011; Davis et al. 2011; Cappellari 2016). Follow up studies of some ETGs have searched for neighbors which could serve as external gas sources, often finding plausible companions (Duc et al. 2007; Crocker et al. 2008). Yet the high occurrence rate of dusty ETGs presents a challenge to the external origin hypothesis. Martini et al. (2013) concluded that if 60% of all ETGs contain large amounts of dust and the destruction timescale is not more than 10$^7$ – 10$^8$ years, then the merger rate between ETGs and gas-rich dwarf galaxies must be orders of magnitude larger than the predicted value (Stewart et al. 2009). Uncertainties in merger rates and dust lifetimes could make external accretion a viable gas and dust source, but Martini et al. (2013) proposed that the more likely solution is a combination of external and internal processes.

We can identify which processes produce the majority of the observed dust through a comparison of stellar and gas-phase metallicities (Martini et al. 2013). If evolved stars eject material into the ISM, we expect the metallicity to be similar to the stellar abundances. If low metallicity dwarf galaxies have been accreted, we expect to sub-stellar gas-phase oxygen abundance as the dwarf galaxies would dilute the metallicity. We also expect to find sub-stellar metallicities if a combination of the two production mechanisms are important (Bresolin 2013).

It is not straightforward to measure the parameters of stellar population composite stellar spectra. Since the 1980’s, models of spectral indices (Burstein et al. 1984; Worthey et al. 1994) have been used to broadly determine the ages and metallicities of stellar populations. Spectral indices are informative but ignore a great deal of information. By modeling the entire spectrum it is possible to achieve greater sensitivity to trace elements (Conroy et al. 2013) and better quantify population parameters. This approach requires high quality stellar spectral models, such as those from the MILES library (Sánchez-Blázquez et al. 2006) and the extended IRTF library (Villanueve et al. 2017). Recently Conroy & van Dokkum (2012) developed such a program and have studied the underlying stellar populations of ETGs and globular clusters (Conroy et al. 2014, 2018), finding good agreement with results from previous Lick index fitting techniques, such as Graves & Schiavon (2008). We employ similar methods to determine the stellar properties of the ETGs included in this work.

Gas-phase metallicities can be spectroscopically determined through a variety of techniques. The direct method, often referred to as the $T_e$ method, provides the most reliable and accurate abundance diagnostic (Dinerstein 1990). In this approach, one measures the electron temperature through measurements of auroral and nebular lines. Detecting auroral lines is extremely difficult, especially at high metallicity. Strong-line methods were subsequently developed to provide metallicity estimates for galaxies without detectable auroral lines (Allibon et al. 1979; Pagel et al. 1979) and calibrated by theoretical (McGaugh 1991; Zaritsky et al. 1994; Kewley & Dopita 2002) and empirical means (Pettini & Pagel 2004; Marino et al. 2013). Strong-line methods employ nebular emission lines, such as [O ii]λ3727, [O iii]λ5007, and [N ii]λ6583, along with prominent Balmer lines.

In this paper we present strong-line metallicity measurements of three dusty early-type galaxies observed with The Multi-Object Double Spectrographs (MODs) (Pogge et al. 2010) on the Large Binocular Telescope (LBT). We also include data from similar studies of ETG abundances by Athey & Bregman (2009), Annibali et al. (2010), and Bresolin (2013) where applicable. While few studies have compared stellar and nebular abundances for the same galaxies, we note that Zahid et al. (2017) compare stellar and nebular abundances for star-forming galaxies. After a brief description of our data in Section 2, in Section 3 we fit the background stellar population, determine line fluxes, and calculate metallicities. In Section 4 we compare the gas-phase metallicities to the stellar metallicities and present the mass-metallicity relationships. Section 5 discusses the potential for internal dust production or external accretion. Finally, we summarize our results in Section 6.

2 METHODS

Martini et al. (2013)’s study of archival Spitzer and HST data found that approximately 60% of ETGs contained $\geq$ 10$^5$ M$_\odot$ of dust. To probe the nature of this interstellar material, we selected three dusty ETGs for follow up spectroscopy: NGC 2768, NGC 3245, and NGC 4694. These galaxies were chosen due to their proximity, strong presence of dust lanes in HST imaging, and weak (NGC 2768) or no evidence (NGC 3245 & NGC 4694) of an AGN. The filamentary dust structures, H I and CO kinematics, and molecular gas masses of these galaxies all suggested external accretion
as the source of interstellar dust (Simões Lopes et al. 2007; Oosterloo et al. 2010; Crocker et al. 2008).

We observed the three ETGs between January 2014 and February 2015 with MODS1 on the LBT. The spectrograph’s dichroic divides incoming light into red and blue channels at ~5650 Å. The blue spectrum has a lower bound of ~3200 Å and the red an upper bound of ~10,000 Å. Both channels have a resolution of $R \sim 2000$ for a 0.6” slit. The long-slit was not oriented along the parallactic angle for NGC 2768 in order to measure extended emission-line regions. As these galaxies are well resolved, they did not require good seeing and thus were observed in poorer conditions. A log of our observations and the basic properties of our sample are listed in Table 1.

A detailed discussion of the MODS data reduction pipeline can be found in Berg et al. (2015). In short, we use the modsCCDRed$^1$ and modsIDL$^2$ suites to bias subtract, flat field, median combine, remove sky lines, and extract 1D spectra. Outside of the MODS program, we apply a response curve to correct for Galactic extinction. We employ the Cardelli et al. (1989) reddening law with $R_v = 3.1$ and use dust maps from Schlegel et al. (1998).

### 3 ANALYSIS

#### 3.1 Stellar Population Modeling

After reducing the data, we model our spectra with alf, an “absorption line fitting” program (Conroy & van Dokkum 2012; Conroy et al. 2018), based on the MIST isochrones (Choi et al. 2016), and optical and NIR empirical stellar libraries (Sánchez-Blázquez et al. 2006; Villuame et al. 2017). We use alf to determine stellar abundances and to better measure the emission lines. In particular, stellar absorption features can hide emission lines such as Hα and Hβ.

Given some initial conditions, alf constrains 46 fit parameters (including stellar abundances, age, and emission line fluxes) and produces a corresponding model spectrum. Figure 1 shows the three galaxies’ observed spectra, the alf model, and the residual between the two. Telluric features in the A and B bands have been masked, as well as a noisy region between 9200 Å and 9600 Å. We note the flatness of the residual spectrum—a testament to the fit quality. Residuals increase blueward of 4000 Å where the density of atomic lines increases. NGC 4694’s velocity dispersion (Wegner et al. 2003) falls below the lower limit of alf’s models (100 km/s). We therefore smooth the spectrum by a Gaussian with a velocity full-width-half-maximum of 350 km/s.

While the program reports 18 stellar abundance parameters, resolved and unresolved spectral features cause some elements to be better constrained than others. We focus on C, N, O, and Mg, which should be among the best measured. We convert these abundances from [X/H] to [X/Fe], as suggested in Conroy et al. (2018). Select best-fit population parameters are listed in Table 2. The age quoted here is a mass-weighted combination of the dominant and young stellar components.

Though the fits shown in Figure 1 include emission line features, a subsequent alf routine uses the fit parameters to produce solely stellar spectral models. These alf models are of higher resolution than our observed spectra. We convolve the stellar models with Gaussians to match the MODS instrumental resolution. We then continuum-normalize our observed spectra and convolve to alf’s flux units. Finally, we subtract the model stellar spectra from the observed spectra, leaving the emission line spectra of our three objects (Figure 2).

#### 3.2 Stellar Masses and Star Formation Rates

We calculate stellar masses using WISE W1 magnitudes and the M/L relationship derived by Simonian & Martini (2017). We choose this relationship because that study also focused on dust. Our stellar masses agree with available S4G values and the results of similar calculations from Cluver et al. (2014).

We also derive star formation rates (SFRs) for our sample with the infrared (IR) and ultra-violet UV star formation relationships from Leroy et al. (submitted), who consolidates the work of Kennicutt & Evans (2012) and

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1. [http://www.astronomy.ohio-state.edu/MODS/Software/modsCCDRed](http://www.astronomy.ohio-state.edu/MODS/Software/modsCCDRed)
2. [http://www.astronomy.ohio-state.edu/MODS/Software/modsIDL/](http://www.astronomy.ohio-state.edu/MODS/Software/modsIDL/)
Figure 1. Top panel: MODS spectra (black line) with alf model of emission and absorption features over plotted (red, dashed line). Fluxes have been normalized. Telluric A and B bands, as well as a noisy region near 9400Å, have been masked. Bottom panel: Residuals between observed and model spectra (grey line). Residuals for NGC 3245 and NGC 2768 have been shifted by 30% and 60%, respectively.

Figure 2. Normalized emission line spectra of NGC 2768, NGC 3245, and NGC 4694. Spectra have been shifted to rest-frame wavelengths and prominent lines are labeled. The telluric A and B bands, as well as the noisy region near 9400Å, have been masked.

Jarrett et al. (2013). Star formation can be traced by UV light emitted by the young stellar population and IR light as dust particles absorb UV photons and re-emit them at redder wavelengths. Due to the dusty nature of these galaxies, we expect to see evidence of star formation in both the IR and UV. Therefore, we derive SFRs using a combined IR and UV indicator. We take IR and FUV/NUV magnitudes from the WISE and GALEX archives, respectively. Both W4 (22 μm) and W3 (12 μm) bands trace SF efficiently. W4 provides the best SF signal but has low sensitivity and a bias towards luminous IR galaxies. W3 has greater sensitivity than W4 and can detect dimmer galaxies. Large galaxy samples often derive SFRs from W3 magnitudes as they better represent the population. We choose to use W3 as our IR indicator because we have included a large sample of galaxies from previous work.

If no dust were present we would expect the NUV and FUV star formation indicators to be identical. We find that the NUV band contributes more to the total UV star formation indicator than the FUV band and therefore choose...
NUV as the UV indicator. We sum the IR and UV components to give the total SFR. The stellar masses and SFRs are listed in Table 1.

Table 1 also includes the objects’ specific star formation rate (sSFR), where sSFRs = SFR/M⊙. We find values of 1.4 × 10^{-12} yr^{-1} for NGC 2768, 2.5 × 10^{-12} yr^{-1} for NGC 3245, and 8.8 × 10^{-12} yr^{-1} for NGC 4694. Circumstellar dust in old ETGs will mimic a sSFR of 2 × 10^{-12} yr^{-1} (Simonian & Martini 2017), so W3 and W4 fluxes can not be trusted as SFR indicators below this threshold. NGC 2768 falls below this value, NGC 3245 near it, and NGC 4694 above it. Further, we expect that we overestimate these SFRs due to the old stellar population. Old stars within galaxies heat dust grains which inflate the IR luminosity and thus the measured SFR (Catalán-Torrecilla et al. 2015). While their SFRs are low, all objects do show evidence of ongoing SF based on far-infrared emission (Martini et al. 2013).

3.3 Gas-Phase Abundances
To derive the emission line fluxes, we fit spectral features with Gaussian profiles. We use a non-linear, least squares minimization routine to fit the lines and surrounding continuum. We allow for freedom in line height, width, and a small range of central wavelength. The triple line system of [N\textsc{ii}]6549, Hα, and [N\textsc{ii}]6583 is fit with three Gaussians of fixed width. Flux values ascertained from these Gaussian fits agree well with simple summations. We derive line flux errors from the continuum RMS.

We do not detect the auroral lines necessary for the direct method. Instead, we employ lines commonly used in strong line methods, [O\textsc{iii}]λ4372, Hβ, λ4861, [O\textsc{ii}]λ4007, Hα, and [N\textsc{ii}]λ6583, with the following diagnostic emission line ratios:

N2 = [N\textsc{ii}]λ6583/H\alpha
O3N2 = [O\textsc{iii}]λ4007/H\beta/[N\textsc{ii}]λ6583/H\alpha
N2O2 = [N\textsc{ii}]λ6583/[O\textsc{ii}]λ4372

Given the dusty nature of these galaxies, we expect that dust reprocessing has shifted some blue light to redder wavelengths. We quantify the amount of reprocessing through the Hα to H\beta ratio, which should intrinsically exhibit the Case B recombination value of Hα/H\beta = 2.87 at T_e = 10^4 K. We de-redden the spectra under this assumption according to the extinction law from Cardelli et al. (1989). The N2 and O3N2 metallicity indicators are relatively insensitive to reddening as they employ adjacent lines. Table 3 contains de-reddened flux values for the features used in the subsequent strong-line analysis.

NGC 2768 presents a unique reddening correction challenge due to the impact of atmospheric dispersion on the data. Instead of aligning the slit with the galaxy’s parallactic angle, the slit was oriented with respect to the molecular gas features (Table 1). Compounding this slit position with low hour angle observations caused a significant amount of blue light loss. We study the evolution of the Hα/H\beta ratio over images of progressing hour angles. The changing value confirms that atmospheric dispersion impacts our data. While the dispersion should evenly scatter the smoothly distributed starlight in and out of the slit, we do not necessarily recover photons from H\alpha regions due to their non-uniform distribution throughout the galaxy. Given the effects of atmospheric dispersion, we cannot reliably determine NGC 2768’s reddening and the atmospheric dispersion correction. In our analysis we will put more weight on indicators which employ adjacent lines because they are least sensitive to the effects of dust reprocessing and atmospheric dispersion. Observations of NGC 3245 and NGC 4694 were oriented along the galaxies’ parallactic angles.

\texttt{alf} also provides additional measurements of the emission lines. The routine fits each emission line with a Gaussian profile and adopts free parameters for each ionization species. Accepted line ratios for that species are taken from Cloudy models. For example, \texttt{alf} returns a single [N\textsc{ii}] flux value and assumes a fiducial ratio between the λ6547 and 6583 lines. Our derived fluxes agree reasonably well with those fit by \texttt{alf}. The discrepancies appear to be because \texttt{alf} does not account for reddening and does not make special considerations for blended lines. We do not use \texttt{alf}'s flux values and instead use our measurements (Table 3) to derive strong-line metallicities.

The most common strong-line diagnostics include N2, O3N2, and N2O2, defined above. Brown et al. (2016) assesses the performance of these indicators in a study of ~200,000 star-forming galaxies from the Sloan Digital Sky Survey. They conclude that O3N2 is the most accurate indicator, followed closely by N2O2. They note N2O2's good performance at high metallicities, an echo of Kewley & Dopita (2002) who show that this indicator has a much tighter correlation with true abundances for objects.

| Ion/Indicator | NGC 2768 | NGC 3245 | NGC 4694 |
|---------------|----------|----------|----------|
| [O\textsc{ii}]λ4372 | 6.15 ± 0.38 | 3.54 ± 0.33 | 2.86 ± 0.16 |
| H\beta λ4861 | 1.00 ± 0.08 | 1.00 ± 0.11 | 1.00 ± 0.07 |
| [O\textsc{iii}]λ4007 | 1.62 ± 0.13 | 0.97 ± 0.10 | 0.33 ± 0.04 |
| [O\textsc{ii}]λ4630 | 0.46 ± 0.07 | 0.08 ± 0.03 | 0.04 ± 0.01 |
| Hα λ6563 | 2.86 ± 0.17 | 2.86 ± 0.23 | 2.86 ± 0.13 |
| [N\textsc{ii}]λ6583 | 3.57 ± 0.21 | 2.34 ± 0.19 | 0.97 ± 0.05 |
| PP04 N2 | 8.95 | 8.85 | 8.63 |
| PMC09 N2 | 9.15 | 9.00 | 8.70 |
| PP04 O3N2 | 8.69 | 8.71 | 8.73 |
| KD02 N2O2 | 9.03 | 9.05 | 8.92 |
| Brown N2 | 9.22 | 9.12 | 8.89 |
| Brown O3N2 | 8.99 | 9.00 | 9.03 |
| Brown N2O2 | 9.16 | 9.19 | 9.04 |
with $12 + \log(O/H) > 8.6$. The N2 indicator under performs O3N2 and N2O2 as it worsens at higher metallicities. Overall, however, Brown et al. (2013) concluded that all three relationships fair well and none excel far over the others. We continue in our analysis with these three indicators, adopting metallicity definitions from Pettini & Pagel (2004) (PP04), Pérez-Montero & Contini (2009) (PMCO9), and Kewley & Dopita (2002) (KD02), as well as the new calibrations from Brown et al. (2016). The middle section of Table 3 contains the metallicity results for our galaxies.

Metallicities are also dependent upon the star formation rate of a galaxy (Ellison et al. 2008b; Lara-López et al. 2010; Mannucci et al. 2010). Recent work by Brown et al. (2016) re-calibrates the above diagnostics against direct method abundances while accounting for the SFR dependence of the mass-metallicity relationship. Their new metrics depend on $\Delta \log(sSFR) = \log(sSFR) - \log(sSFR)_{M_\odot}$ (Salim et al. 2007), where $\log(sSFR)_{M_\odot}$ is the median $\log(sSFR)$ of galaxies at a given $M_\star$. We re-calculate our metallicity indicators according to the N2, N2O2, and O3N2 calibrations specified in Brown et al. (2016). ETGs in our sample, as well as those of Athey & Bregman (2009) (9 ETGs observed with the Michigan-Dartmouth-MIT 2.4 m Hiltner Telescope), Annibali et al. (2010) (57 ETGs observed with the 1.5 m ESO-La Silla telescope), and Bresolin (2013) (NGC 404 observed by the Gemini Multi-Object Spectrograph at the Gemini North telescope), fall near or beyond the high mass limit of Brown et al. (2016)’s population and far below the $\Delta \log(sSFR)$ lower limit. We do not extrapolate the relationships to such low $\Delta \log(sSFR)$ as there is little to no data in that regime. Instead, we choose to assign all galaxies a $\Delta \log(sSFR) = -0.25$, the lowest bin included in Brown et al. (2016). This is a reasonable assumption because the dependence on sSFR lessens in higher mass galaxies, especially for the O3N2 indicator. These metallicity values are listed in the bottom section of Table 3. If we were to use the Brown et al. (2016) values for the actual $\Delta \log(sSFR)$, all indicators would show much higher oxygen abundances.

### 3.4 Alternative Ionization Sources

Gas-phase metallicities such as KD02 and PP04 are calibrated through abundance measurements of extragalactic H\textsc{ii} regions and photoionization models. However, ETGs contain many other ionization sources, such as nuclear activity, shocks, cosmic rays, magnetohydrodynamic waves, and old, hot stars. We evaluate the potential impact of each of these ionization sources on our metallicity measurements.

First, we assess the star-forming nature of our objects and their potential AGN contamination by placing them on the classic Baldwin-Phillips-Terevich (BPT) diagram (Baldwin et al. 1981). BPT diagrams typically include [O iii] $\lambda$5007, as this state has a higher ionization energy than other prominent strong lines. The hardness of the radiation field sets the [O iii] $\lambda$5007/$H\beta$ ratio. A high value implies more energetic photons and suggests AGN activity. We determine our galaxies’ principle energy and ionization sources by locating them in log([O iii] $\lambda$5007/$H\beta$) vs. log([N ii] $\lambda$6583/Hα) space and comparing their position to the Kauffmann et al. (2003) and Kewley et al. (2006b) star-formation/AGN boundaries. Star formation dominates galaxies which fall below these two curves, while those above may be classified as LINERs or AGNs. If a galaxy falls within the AGN locus, we expect that its off-nuclear line ratios would lie closer to the star-forming region.

In addition to spectra of the entire galaxy (extraction width 24\arcsec), we extract multiple smaller, one-dimensional spectra from each galaxy: one on the nucleus and two to four off-nuclear positions of width 4\arcsec. We apply the analysis described in Section 3.1 and 3.3 to each. Figure 3 shows the [O iii] $\lambda$45007/$H\beta$ and [N ii] $\lambda$6583/Hα ratio along the spatial dimension (lighter, smaller markers), as well as the values of the entire slit (darker, larger markers). $H\beta$ was not detected in some off-nuclear spectra. We find that off-nuclear line flux measurements concur with nuclear and full galaxy line fluxes. The remainder of our analysis employs just the full galaxy spectra.

Figure 4 shows our galaxies on a BPT diagram. NGC 4694 is clearly in the star formation locus. NGC 3245 is close to the extreme star formation limit line of Kewley et al. (2006b). NGC 2768 is in the LINER region, as are ETGs from previous studies by Athey & Bregman (2009) and Annibali et al. (2010) (grey markers). We applied reddening corrections and calculated metallicities for objects in those studies as we did for our objects (see Section 3.3). The line ratios for NGC 2768, and the galaxies in Athey & Bregman (2009) and Annibali et al. (2010), suggest that there is AGN contamination in the [N ii] $\lambda$6583 line. As mentioned in Section 2, we expect some AGN activity in NGC 2768. The off-nuclear spectra show slightly lower [N ii] $\lambda$6583/Hα ratios but similar [O iii] $\lambda$45007/$H\beta$ values (Figure 3) and would remain in the LINER region. The line ratios for NGC 3245 also suggest nuclear activity, though their off-nuclear [N ii] $\lambda$6583/Hα values are similarly high and do not decrease to the ratios characteristic of star formation.

Alternatively, emission from old, hot stars could explain NGC 2768 and NGC 3245’s positions on the BPT diagram. Post-asymptotic giant branch (pAGB) stars are known to be sources of ionizing photons (Binet et al. 1994), especially among old stellar populations such as those seen in ETGs. Integrated field studies have convincingly shown that the line ratios and line fluxes do not decrease with radius as rapidly as expected if nuclear activity were the only way to produce LINER-like ratios (Sarzi et al. 2010). Belfiore et al. (2016) studied the location of many ETGs on the BPT diagram and found that they can lie near or beyond the SF/LINER threshold. They conclude that many galaxies dominated by SF are misclassified as active because of this overlap.

In addition to pAGB stars, ionization by fast or slow shocks can influence the observed line fluxes. Previous work by Crocker et al. (2008) and Sarzi et al. (2010) suggested that the line ratios in NGC 2768 could be affected by shock ionization in the central region. While their SAURON project used [O iii] $\lambda$45007/$H\beta$ and [N ii] $\lambda$6583, 5200/$H\beta$ ratios as diagnostic tools, their wavelength coverage does not extended to redder lines such as [N ii] $\lambda$6583. We use the MAPINGS III shock models (Allen et al. 2008) to determine the potential effect of shock ionization on the [N ii] $\lambda$6583/$H\alpha$ ratio. The Veilleux & Osterbrock (1987) log([O iii] $\lambda$45007/$H\beta$) vs. log([N ii] $\lambda$6583/Hα) diagnostic diagrams for solar abundance shock models place NGC 2768 on the edge of low velocity, solar shock models. Similar diagnostic diagrams for different atomic abundances show large variations between
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Figure 3. Ratio of [O III]λ5007/Hβ and [N II]λ6583/Hα for different slit positions and the entire galaxy slit for NGC 2768 (left), NGC 3245 (middle) and NGC 4694 (right). The bars in the x-dimension represent the region summed along the slit. The bars in the y-dimension represent the uncertainty on the ratio values. When not visible, error bars are smaller than the markers. Hβ was not detected in all spectra and the [OIII]λ5007/Hβ values have been excluded in these cases.

Figure 4. BPT diagram including star formation/AGN boundaries from Kauffmann et al. (2003) (solid line) and Kewley et al. (2006b) (dashed line). Error bars on points from this work are smaller than the data points. We also mark the locations of alternate ionization sources (the extra heat point falls off of the plotted region). The SMC shock models represent constant magnetic parameter (0.5-10 μG cm³/², left to right black lines) and constant shock velocity (125-1000 km s⁻¹, top to bottom red lines). The cosmic ray and extra heat line ratios are from Ferland et al. (2009) and the SMC shock models are from the MAPPINGS III library (Allen et al. 2008). See Section 3.4 for further details.

low metallicity shock models and super-solar shock models (Allen et al. 2008, Figure 21). The shock model for an SMC like galaxy (low metallicity) with velocities of 125-1000 km s⁻¹ and magnetic parameters of 0.5-10 μG cm³/² is included in Figure 4. This low metallicity shock model occupies a much lower log([N II]λ6583/Hα) space than our objects. While shock ionization may be present, the MAPPINGS III models demonstrate that shocks cannot make low metallicity gas appear solar or super solar.

Collisional heating from cosmic rays and dissipative magnetohydrodynamic waves (“extra heat”) could also contribute to low-ionization emission line fluxes. Ferland et al. (2009) modeled spectra which reproduced H₂/Hα ratios for both extra heating and cosmic ray cases to within a factor of two. We take line fluxes from their work and calculate the [O III]λ5007/Hβ and [N II]λ6583/Hα ratios characteristic of these two ionization mechanisms. We include these values on the BPT diagram in Figure 4—though the extra heat case falls off of the plotted region. Given that both models occupy regions not populated by our galaxies, we rule out extra heating and cosmic rays as potential ionization sources.

Finally we consider ionization by single degenerate (SD) Type Ia supernovae progenitors (Woods & Gilfanov 2014). In this scenario a white dwarf (WD) accretes matter from its main sequence or red giant companion until the WD explodes as a supernovae. If this formation theory is correct and SD supernovae occur at the expected rate, then the accreting WD population should be extremely luminous. In young populations (< 4 Gyrs) of temperatures 10⁵ – 10⁶K, SD progenitors could be the dominant ionization source. To determine if WDs play an active role in ionizing gas, Woods & Gilfanov (2014) develop diagnostic tools which utilize [N I], [O I], and [C I]—emission lines enhanced through high temperature ionization. We reproduce their [O I]λ6300/Hα vs. [O III]λ5007/Hβ diagnostic diagram in Figure 5. Their SD models produce [O I]λ6300/Hα ≥ ~ 0.5 for T⁰eff = 10⁶K and solar gas-phase metallicity. Our sample, as well as that of Athey & Bregman (2009) and Annibali et al. (2010), have lower values of these ratios and do not show evidence for a contribution from hot SD progenitors. Woods & Gilfanov (2014) include a sub-sample of points from Annibali et al. (2010) and come to a similar conclusion, though they do not rule out the SD case due to uncertainties in the line fluxes. Our line fluxes have lower
We adopt this minimum uncertainty on our stellar abundances in all further analysis. Our galaxies lie within 0.1-0.2 dex of the ETG stellar abundance trends found by Conroy et al. (2014). NGC 4694 differs the most. This could be because NGC 4694 has the youngest stellar population (Table 2), which sets it apart from a typical ETG. At such young ages the abundance sensitivity also decreases and abundances are more difficult to measure. The disagreement between some data points and the models could be due to abundance gradients within the galaxies. We expect the uncertainty due to this effect to be ∼0.1 – 0.2 dex (Kudritzki et al. 2014; Bresolin et al. 2016).

We directly compare the stellar and gas-phase metallicities of our ETGs in Figure 7. We adopt a solar oxygen abundance of 12 + log(O/H)⊙ = 8.85 (Villante et al. 2014). We derive the stellar oxygen abundance, [O/H], from αf [Fe/H] and [O/Fe] values and take Brown et al. (2016)’s O3N2 calibration to be the best gas-phase oxygen abundance. We find that the gas-phase and stellar metallicities are consistent within 1-2σ. Finally, we compare our stellar and gas-phase abundances to work by Bresolin et al. (2016) on stellar abundances for nearby galaxies from blue supergiants (BSGs) and the mass-metallicity relationship. Figure 8 shows the gas-phase O3N2 metallicity values for each galaxy (solid markers), the best-fit [O/H] stellar abundances (open markers), stellar abundances derived from BSGs in Kudritzki et al. (2014), Hosek et al. (2014), and Bresolin et al. (2016), and the mass-metallicity relation from Andrews & Martini (2013). The stellar abundances agree with the nebular and stellar abundance trends, as well as the measured gas-phase metallicities for their respective galaxies.

Based on the results shown in Figures 7 and 8, we do not find evidence of gas-phase oxygen abundances that are significantly lower than that of the stellar population. This observation argues strongly against external accretion of low metallicity dwarf galaxies as the source of dust and gas in ETGs.

4 RESULTS

4.1 Comparing Stellar and Gas-Phase Metallicities

We compare the stellar and gas-phase metallicities to determine if the ionized gas is consistent with internal production or external accretion. The main stellar abundances we consider are [Fe/H], [C/Fe], [N/Fe], [O/Fe], and [Mg/Fe], based on a similar analysis by Conroy et al. (2014) of stacks of SDSS ETGs binned by velocity dispersion. They found that N, C, and Mg trace O, as expected from models of chemical evolution. We compare our best-fit values to their abundance measurements in Figure 6 where we have plotted their results vs. stellar mass, rather than velocity dispersion. The model stellar abundances include 0.05 dex of systematic errors (Conroy et al. 2014). We adopt this minimum uncertainty on our stellar abundances in all further analysis. Our galaxies lie within 0.1-0.2 dex of the ETG stellar abundance trends found by Conroy et al. (2014). NGC 4694 differs the most. This could be because NGC 4694 has uncertainties and our results are correspondingly less ambiguous.

We conclude that the ionized gas in NGC 4694 is due to photionization by young stars, while there is some contribution from old stars in NGC 3245 and these stars may dominate in NGC 2768. We do not find any evidence that AGN, cosmic ray heating, extra heat, shocks, or hot SD progenitors significantly affect the line ratios.

4.2 The Mass-Metallicity Relationship

We compare our metallicity determinations to the mass-metallicity relation (MZR) (Tremonti et al. 2004; Kewley & Ellison 2008; Andrews & Martini 2013) in Figure 9. The location of our sample in mass-metallicity space with respect to empirical models is a separate way to determine how their gas-phase abundances relate to a typical galaxy of similar mass. Figure 9 plots the PP04 N2 (top), PP04 O3N2 (middle), and KD02 N2O2 (bottom) metallicity indicators with corresponding relationships from Kewley & Ellison (2008). We re-calibrate all data and MZRs to the PP04 O3N2 relationship (Kewley & Ellison 2008) as the PP04 O3N2 MZR shows good agreement with the direct method MZR in the high mass range (Andrews & Martini 2013). All data points fall near their respective models. The O3N2 and N2O2 indicators show tighter relationships than the N2 indicator. We note that many of the N2 points fall outside of the PP04 O3N2 re-calibration range (12 + log [O/H] = 8.05 – 8.8) and that they are an extrapolation of the relationship. None of the objects show signatures of low metallicity gas. Figure 9 includes a sub-sample of points from Athey & Bregman (2009) and Annibali et al. (2010) for which the specified metallicities and masses could be derived. Bresolin (2013)’s N2 and O3N2 measurements of NGC 404 with a mass from Thilker et al. (2010) is also included. The mass-metallicity relationship is correlated with the
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Figure 6. A comparison of alf’s best-fit [N/Fe], [C/Fe], [Mg/Fe], and [Fe/H] values to ETG abundance trends from Conroy et al. (2014).

Figure 7. A direct comparison of stellar and gas-phase metallicites. We adopt a solar oxygen abundance of 8.85 (Villante et al. 2014).

Figure 8. Stellar [O/H] (open symbols) and O3N2 gas-phase oxygen abundances (solid symbols) compared to Andrews & Martini (2013) MZR (green line) and BSG stars from Kudritzki et al. (2014), Hosek et al. (2014) and Bresolin et al. (2016) (blue stars). The O3N2 points have been offset by -0.04 log M_*(M_⊙) for clarity.

Our MZR (Figure 9) shows that these three galaxies possess gas of solar or super solar metallicity. This is also true for other ETGs with data from the literature. No galaxy displays evidence of low metallicity gas.
5 DISCUSSION

One hypothesis to explain the dust and gas in ETGs is minor mergers with low metallicity dwarf galaxies. Alternatively, the dust and gas could be internally produced by mass loss from evolved stars or cooling from the hot phase of the ISM. The relative uniformity of ETG stellar populations, in contrast to the presence of dust and cold gas in only ~60% of the population, is at odds with the internal production hypothesis.

ATLAS3D kinematics and dust morphology data also support external accretion and provide clues to the merger/interaction history of ETGs. In a study of galaxies with the CARMA ATLAS3D CO survey, Alatalo et al. (2013) classify the disturbance of ETGs based on their molecular gas kinematics and morphology. Two of our three objects, NGC 2768 and NGC 4694, appear in their work and were placed into the disc and extremely disrupted classes, respectively. Alatalo et al. (2013) concluded that NGC 4694 belongs to an interacting system which caused its irregular CO distribution and kinematics. These results agree with previous work by Duc et al. (2007) who propose VCC 2062 as the donor tidal dwarf galaxy. Interestingly, they find VCC 2062 has an oxygen abundance of $12 + \log(O/H) = 8.6 \sim 8.7$, approximately solar. Crocker et al. (2008) and Alatalo et al. (2013) also discuss the asymmetric morphology of NGC 2768. They both conclude that the significant misalignment of the kinematic major axes of the ionized gas and stars suggests NGC 2768 has undergone or is currently involved in a minor merger or other accretion event. Though the neighborhood consists of many potential donor galaxies, Crocker et al. (2008) suggest UGC 4808 as the most likely companion.

While there is some circumstantial evidence of minor mergers in these two cases, we do not measure the lower metallicity gas that would be indicative of external accretion. More generally, the minor merger hypothesis requires a very high merger rate. Based on equations by Stewart et al. (2009), Martini et al. (2013) calculate a merger rate of $0.07 \sim 0.2$ Gyr$^{-1}$. Coupled with the short dust destruction timescale, $\tau_{\text{dust}} \sim 2 \times 10^4$ yr (Draine & Salpeter 1979), they predict a dusty ETG fraction of $f_{\text{dust}} < 0.0014 \sim 0.004$ from mergers alone. Minor mergers can not produce the observed dust mass without a significantly higher merger rate or a significantly longer dust destruction timescale.

If minor mergers are the main source of gas and cold dust in ETGs, one might expect gas dilution to cause little change in the overall gas-phase metallicity. This is not the case. While dusty ETGs contain some cold gas, they
do not have the surplus necessary to dilute accreted material beyond detection. Instead, gas from the dwarf galaxy will dilute that of the ETG, lowering the overall metallicity. This post-interaction metallicity drop has been observed for merging systems. Kewley et al. (2006a) and Ellison et al. (2008a) compare the MZRs of galaxy pairs and field galaxies. They find that the pairs have systematically lower metallicities, as interactions trigger gas flows which redistribute metal poor gas. We expect interacting ETG to show similar metallicity trends. Bresolin (2013) predict the post-merger gas-phase metallicity of NGC 404 from H I observations (del Río et al. 2004) and the star formation history (Williams et al. 2010). They conclude that even after 0.6 Gyr of enhanced star formation, the gas-phase metallicity of the ETG will remain sub-stellar by tenths of a dex. Our solar gas-phase metallicities are inconsistent with the gas dilution and metal depletion expected from the merger scenario.

Our metallicity measurements are in excellent agreement with internal production of dust and gas from evolved stars or cooling from the hot phase of the ISM. While this hypothesis also struggles to produce the observed dust masses and the fraction of dusty ETGs, an ISM hot-phase temperature of $10^5$ K or rapid cooling could lower the dust destruction timescales enough to bridge the dust mass gap (Martini et al. 2013; Mathews & Brighenti 2003). Pulido et al. (2018) use CO and X-ray emission from ETGs to link molecular gas content and short cooling timescales. Their data agree better with an internal rather than external origin and they consequently conclude that the molecular gas condenses from the hot atmosphere. They propose that X-ray bubbles from the central AGN lift gas away from the nucleus and cause molecular gas to condense and cool as it falls inward. X-ray measurements of our sample and other ETGs with and without cold gas and dust would be valuable to determine if there is a correlation between shorter cooling times and the presence of cold gas and dust.

6 SUMMARY

We have presented long-slit spectroscopy of three dusty early-type galaxies with MODS on the LBT and measured their gas-phase and stellar abundances. Our main results are:

1. The emission line flux ratios do not vary significantly along the slit, so the metallicity derived from the integrated spectra will be representative of the entire galaxy and not just the nucleus.

2. The emission lines are predominantly ionized due to stars (either young or pAGB) and not subject to other ionization sources that may impact the metallicity measurements. NGC 2768 and NGC 3245 fall near the LINER region while NGC 4694 falls on the SF sequence. We expect some signatures of nuclear activity in NGC 2768, but the off-nuclear line ratios also fall within the LINER region, which points to ionization by the old stellar population.

3. We rule out alternative ionization by cosmic rays and extra heating due to the models’ occupation of a different BPT parameter space than our objects. MAPPINGS III shock models suggest that solar metallicity shocks may be present in NGC 2768. We determine that these shocks will not disguise low metallicity gas as solar or super-solar gas. We conclude that our derived abundances reflect the true gas-phase metallicity.

4. We derive gas-phase oxygen abundances from the N2, O3N2, and N2O2 strong-line indicators and calibrate these results to account for their SFR dependence. We derive stellar oxygen abundances through alf’s stellar population modeling. We find that the gas-phase and stellar metallicities are in good agreement (Figures 7 and 8). Additionally, all objects’ gas-phase metallicity values lie along the MZR (Figure 9) and do not show the lower metallicities expected from interactions or mergers with lower-metallicity dwarf satellites.

5. Although the irregular dust and gas morphology and kinematics suggests a merger origin, our results clearly show that the gas and stellar abundances are consistent. This strongly supports internal production by the old stellar population and/or cooling from the ISM rather than external accretion. Future X-ray observations to measure the cooling from the hot phase of the ISM would be valuable to investigate why only ~60% of otherwise similar ETGs have gas and dust.

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