OUTLIERS FROM THE MASS–METALLICITY RELATION. II. A SAMPLE OF MASSIVE METAL-POOR GALAXIES FROM SDSS

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ABSTRACT

We present a sample of 42 high-mass low-metallicity outliers from the mass–metallicity relation of star-forming galaxies. These galaxies have stellar masses that span \( \log(M_*/M_\odot) \sim 9.4 \) to 11.1 and are offset from the mass–metallicity relation by \( -0.3 \) to \(-0.85\) dex in \( 12 + \log(O/H) \). In general, they are extremely blue, have high star-formation rates for their masses, and are morphologically disturbed. Tidal interactions are expected to induce large-scale gas inflow to the galaxies’ central regions, and we find that these galaxies’ gas-phase oxygen abundances are consistent with large quantities of low-metallicity gas from large galactocentric radii diluting the central metal-rich gas. We conclude with implications for deducing gas-phase metallicities of individual galaxies based solely on their luminosities, specifically in the case of long gamma-ray burst host galaxies.

Key words: galaxies: abundances -- galaxies: evolution

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1. INTRODUCTION

Star-forming galaxies fall on a luminosity–metallicity relation such that more luminous galaxies tend to have higher gas-phase metallicities (the proxy for which is typically the oxygen abundance in units of \( 12 + \log(O/H) \)). This relation is observed to hold—shifted to lower metallicities—at redshifts as high as \( z \sim 3.5 \) (Erb et al. 2006; Maiolino et al. 2008), and its scatter decreases to \( \sim 0.15\) dex at \( z \sim 0\) when galaxy stellar mass replaces luminosity in the relation (Tremonti et al. 2004). Most commonly accepted theories as to the origin of the mass–metallicity relation have as a central proposition that low-mass galaxies are metal deficient, rather than that high-mass galaxies are metal enhanced (Larson 1974; Dalcanton 2007; Finlator & Davé 2008). In fact, there is some evidence that the mass–metallicity relation may flatten at large stellar masses, \( \log(M_*/M_\odot) \sim 10.5 \) (e.g., Tremonti et al. 2004), though it is unclear to what extent this flattening is due to a saturation of the metallicity indicator used at high oxygen abundances (see, e.g., Kewley & Dopita 2002; Bresolin 2006; Kewley & Ellison 2008).

Because most star-forming galaxies do lie on a mass–metallicity locus, we can learn about the gas-phase metallicity evolution of galaxies by studying the properties of galaxies that do not fall on the relation. In Peeples et al. (2008, hereafter Paper I), we explored the population of low-mass high-metallicity outliers, and postulated that these metal-rich dwarf galaxies have low gas fractions, and are therefore nearing the end of substantial epochs of star formation. Here, we investigate the other corner of the mass–metallicity plane by asking what we can learn about the evolution of massive galaxies from the properties of the high-mass low-metallicity outliers.

As shown in Figure 1, we find 42 low-metallicity high-mass galaxies with masses ranging from \( \log(M_*/M_\odot) \sim 9.4 \) to 11.1 and offsets from the central mass–metallicity relation of \(-0.3\) to \(-0.85\) dex. We describe in Section 2 how we selected this sample and verified the galaxies’ outlier status. In Section 3, we describe the physical properties of these galaxies and discuss possible origins for their low oxygen abundances. Specifically, we find that they have highly disturbed morphologies strongly suggestive of merging or post-merging systems, are extremely blue, and have high specific star-formation rates (SSFRs). We summarize our conclusions and state some implications of these findings in Section 4.

2. SELECTING HIGH-MASS LOW-METALLICITY GALAXIES

We began with a sample of \( \sim 110,000 \) star-forming galaxies from the Sloan Digital Sky Survey (SDSS) Data Release 4 (Adelman-McCarthy et al. 2006) with gas-phase abundances measured by Tremonti et al. (2004) and stellar masses derived using the techniques of Kauffmann et al. (2003). High-luminosity outliers from the mass–metallicity relation can be found in the low-metallicity region of parameter space for one of two reasons: either they have spuriously low derived metallicities or they are genuine outliers. (The third possibility of an object having a spuriously high measured luminosity is much less likely.) In general, the strengths of the visible wavelength oxygen forbidden [O ii] and [O iii] emission lines increase as the oxygen abundance decreases; hence, it is possible for a bright galaxy with a weak active galactic nucleus (AGN) component to appear to have a low oxygen abundance due to contribution from the AGN itself. Likewise, an otherwise “red and dead” galaxy with strong [O ii] emission might be labeled as star forming and, in the Bayesian analysis of Tremonti et al., be assigned an artificially low metallicity. We therefore selected our sample of massive low-metallicity galaxies by first ensuring that they are outliers in the luminosity– and mass–metallicity parameter spaces and then following up with several line-ratio diagnostic tests in an attempt to guarantee that their oxygen abundances relative to the rest of the sample are indeed believable. Images of the galaxies in our final sample are shown in Figure 2 and a summary information is provided in Table 1. As only two of the galaxies in Figure 2 are clearly undisturbed spirals, we note these two galaxies in Table 1, Figure 1, and subsequent figures with a “§” symbol.

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One possible contamination source of these seemingly bright metal-poor galaxies is a low-level AGN, such as a low-ionization nuclear emission-line region (LINER). While it is possible for galaxies with weak AGN activity to also have low oxygen abundances, we choose to not try to disentangle these two effects on the emission line fluxes. Using the line fluxes measured by Tremonti et al. (2004), we put these galaxies on the standard Baldwin, Phillips, & Terlevich (BPT) 1981 diagrams. In particular, as shown in Figure 5, we find that about half of these outliers have strong enough [O\textsc{ii}] λ6300 to place them in the “AGN” region of the BPT diagram. (We note that while the Tremonti et al. (2004) galaxies were chosen to be star forming based on where they fall in the [O\textsc{iii}]/Hβ versus [N\textsc{ii}]/Hα plane, 3.4% of the parent sample galaxies fall in the AGN region of the [O\textsc{iii}]/Hβ versus [O\textsc{i}]/Hα plane.) As expected, the strong-[O\textsc{i}] galaxies also fall close to the “composite” H\textsc{ii}–AGN boundary as defined by Kewley et al. (2006b) in the [O\textsc{iii}]/Hβ versus [N\textsc{ii}]/Hα plane. A visual inspection of the spectra and images of these bogus outliers reveals that many of them are quite red, with only strong [O\textsc{ii}] λ3727 and perhaps weak Hα emission being suggestive of ongoing star formation. Because [O\textsc{i}] λ6300 is a relatively weak line and many of the outliers are clustered near the Kewley et al. (2006b) boundary, we kept galaxies whose [O\textsc{i}]/Hα ratio is within 2σ of the H\textsc{ii}–AGN boundary and whose spectra passed a visual inspection test for, e.g., clear Hβ emission. Representative spectra are shown in Figure 4.

We further tested whether or not the measured metallicities could be due to measurement errors in the relevant line fluxes. Using the Data Release 6 SDSS spectra (Adelman-McCarthy et al. 2008), we subtracted the underlying stellar continuum using the STARLIGHT program (Cid Fernandes et al. 2005), which simultaneously corrects for reddening and extinction using the Cardelli et al. (1989) extinction curves. While the extinction corrections are all small (A_v < 1), the Tremonti et al. line fluxes do not account for reddening, and thus a comparison of widely spaced line ratios produces a systematic offset. We therefore reject seven galaxies for which our measurements strongly disagree with Tremonti et al.’s on the [N\textsc{ii}]/Hα ratio; the difference in each of these cases is such that using the Tremonti et al. ratio would result in a lower 12 + log(O/H) than if ours were used. The added advantage in using the [N\textsc{ii}]/Hα ratio is that this is the ratio used in the Pettini & Pagel (2004) metallicity determination, which we use as discussed below.

2.2. Metallicity Believability

We note that we do not impose a metallicity error cut when selecting these low-metallicity outliers. This is because the errors on Tremonti et al.’s 12 + log(O/H) are not a simple function of metallicity in this range. It has long been recognized that accurately measuring low oxygen abundances (e.g., using R_23) can be tricky due to degeneracies in the ionization parameter, and the line ratios usually used to determine the ionization parameter (e.g., [O\textsc{iii}] λ5007/[O\textsc{i}]/Hα = 3.727) are also dependent on metallicity (McGaugh 1991; Kewley & Dopita 2002). Unfortunately, this means that many metallicity indicators are discontinuous or systematically tend to avoid particular abundance solutions.

We therefore adopted a different approach to ensure that our low-metallicity high-mass outliers genuinely have relatively low oxygen abundances. As discussed in Section 2, we first chose only those galaxies that lie in the H\textsc{ii} region locus of the BPT...
diagrams, and secondly, we discarded those galaxies for which we did not measure a comparable [N II]/Hα ratio to those given by Tremonti et al. Finally, we argue that if these galaxies are truly high-mass low-metallicity outliers, then they should be outliers regardless of how $12 + \log(O/H)$ is measured. (See Kewley & Dopita 2002 and Kewley & Ellison 2008 for thorough discussions of how and why different metallicity calibrations differ.) We therefore used the Tremonti et al. measurements to recalculate $12 + \log(O/H)$ for the entire parent sample using the Pettini & Pagel (2004) method, where the oxygen abundance is given by

$$12 + \log(O/H) = 9.37 + 2.03 \times N2 + 1.26 \times N2^2 + 0.32 \times N2^3,$$

where $N2 \equiv \log([NII] \lambda 6584/H\alpha)$. The main disadvantage of this method is that it uses nitrogen as a proxy for oxygen; however, there are several factors that make it advantageous in these objects. First, it is reddening insensitive because the [NII] $\lambda 6584$ line and Hα are separated by only $\sim 20$ Å. This means that we can safely use the Tremonti et al. measurements and our own measurements without being overly concerned about the reddening corrections. Second, unlike the various of $R_{23}$ methods, the Pettini & Pagel method is both continuous and single valued throughout the metallicity range of interest; there are no “upper” and “lower” branches to concern us. We show the mass–metallicity relation with $12 + \log(O/H)$ measured with the Pettini & Pagel (2004) method in Figure 6. Only one galaxy in the low-[O I] sample did not pass the $12 + \log(O/H)$–$\log M_*$ cuts described in Table 2, suggesting that the remaining galaxies are true low-metallicity outliers.

We have made several other checks for potential systematics. First, spiral (and thus many star-forming) galaxies are known to have metallicity gradients such that their centers have higher abundances than at larger radii (e.g., Zaritsky et al. 1994; Kennicutt et al. 2003). It is therefore reasonable to expect that, on average, spiral galaxies with larger fractions of their light falling in the 3′′ SDSS fiber will have lower integrated metallicities. However, most of our galaxies (see Figure 2) are not spiral galaxies, so we do not expect for this to be a huge effect. Regardless, as shown in Figure 7, while the galaxies

Figure 2. Normalized SDSS $g$-band images of massive low-metallicity galaxies scaled to $40 \times 40$ kpc, with mass decreasing to the right and down from $\log M_* \approx 11.1$ to 9.4. The only two clearly spiral galaxies are the middle two on the top row.
only a small effect, and the offsets we see in metallicity are in our sample do have somewhat high fiber fractions, this is

Figure 3. Example of one of the cuts made to find low-metallicity high-luminosity outliers from the mass–metallicity relation. Plotted is $12 + \log (O/\text{H})$ vs. $M_*$ for the main sample (small light gray points), the 1% objects the lowest log(O/H) in bins of $M_*$ of width 0.4 mag (small black points), and the final sample of high-mass low-metallicity outliers (large gray points). The only two clearly spiral galaxies in the sample are denoted by the “ star” symbol. The histogram shows the 1% threshold in $12 + \log (O/\text{H})$ in bins of $M_*$.

much greater than can be explained by large fiber fractions, which would cause contamination of central high-metallicity H II regions by low-metallicity H II gas at larger galactocentric radii.

Similarly, the final redshift distribution for the galaxies in our sample peaks at higher $z$ than for the main sample; since we have convinced ourselves that this is not purely a fiber fraction effect, it is worrisome that it might partially be a redshift-evolution effect. When the universe was younger, galaxies are expected to have had lower oxygen abundances; the observed mass–metallicity relations for redshifts $z > 0.1$ are systematically shifted to lower metallicity from what is observed for nearby galaxies (Erb et al. 2006; Maiolino et al. 2008). We plot our low-metallicity outliers against the observed mass–metallicity evolution from Maiolino et al. (2008) in Figure 8. While the median redshift for galaxies in our sample is $z \sim 0.17$, the observed oxygen abundances are more typical of redshifts $2.2 \lesssim z \lesssim 3.5$. Though a large amount of scatter in the mass–metallicity relation is both expected and observed (Savaglio et al. 2005; Erb et al. 2006; Kobayashi et al. 2007; Finlator & Davé 2008; Maiolino et al. 2008) at all redshifts, the abundance offsets of our low-metallicity outliers are much more pronounced than the relatively subtle expectations from metallicity evolution with cosmic time.

3. DISCUSSION

To explain these galaxies’ low oxygen abundances, we need to consider the population’s other physical properties. As shown in Figure 9, the galaxies in our sample are all very blue; most—but not all—are also outliers in the galaxy color–magnitude diagram. In Section 3.1, we discuss how this blueness can be attributed to the galaxies’ high SSFRs.

### Table 1

Low-Metallicity Mass–Metallicity Outliers

| R.A. | decl. | $12 + \log (O/\text{H})$ | log $M_*$ | Redshift |
|------|-------|----------------------|-----------|----------|
| 149.9796 | 10.24727 | 8.63 | 11.07 | 0.2423 |
| 255.5060 | 60.79618 | 8.62 | 10.97 | 0.1257 |
| 191.3246 | 4.87648 | 8.33 | 10.94 | 0.1800 |
| 168.6324 | 48.91903 | 8.72 | 10.88 | 0.1116 |
| 197.4139 | 62.76859 | 8.70 | 10.84 | 0.2587 |
| 329.9707 | 1.03852 | 8.59 | 10.83 | 0.2200 |
| 150.2157 | 8.30726 | 8.72 | 10.75 | 0.2290 |
| 148.0473 | 54.31252 | 8.71 | 10.65 | 0.2544 |
| 146.8469 | 53.06987 | 8.67 | 10.63 | 0.2471 |
| 214.2315 | 40.44983 | 8.69 | 10.61 | 0.2060 |
| 196.1901 | 62.40580 | 8.70 | 10.56 | 0.1118 |
| 206.4954 | 11.47993 | 8.60 | 10.54 | 0.2373 |
| 128.9575 | 44.87386 | 8.69 | 10.53 | 0.2264 |
| 158.5174 | 6.20286 | 8.59 | 10.53 | 0.1043 |
| 140.1770 | 0.84295 | 8.69 | 10.49 | 0.2521 |
| 118.9094 | 33.44443 | 8.37 | 10.49 | 0.1413 |
| 170.4012 | 0.54706 | 8.69 | 10.48 | 0.2292 |
| 171.399 | -0.46871 | 8.66 | 10.47 | 0.2270 |
| 158.5274 | 5.51848 | 8.69 | 10.41 | 0.1708 |
| 181.9754 | 12.39080 | 8.67 | 10.41 | 0.2613 |
| 200.4299 | 43.40588 | 8.45 | 10.34 | 0.1950 |
| 126.2741 | 7.21643 | 8.69 | 10.33 | 0.1974 |
| 349.5542 | -0.69060 | 8.68 | 10.29 | 0.2517 |
| 218.7960 | 44.18318 | 8.66 | 10.29 | 0.1276 |
| 250.6480 | 42.39715 | 8.59 | 10.29 | 0.1511 |
| 244.4054 | 35.82085 | 8.64 | 10.20 | 0.2259 |
| 196.2852 | 53.19373 | 8.67 | 10.23 | 0.2719 |
| 146.2970 | 42.64472 | 8.33 | 10.16 | 0.2576 |
| 240.8967 | 31.83226 | 8.17 | 10.12 | 0.1544 |
| 127.9271 | 51.42651 | 8.21 | 10.07 | 0.0813 |
| 153.3421 | 2.58265 | 8.19 | 10.07 | 0.0780 |
| 48.8150 | -7.76643 | 8.25 | 9.95 | 0.0612 |
| 129.3898 | 47.96454 | 8.31 | 9.92 | 0.2152 |
| 234.2552 | 31.44251 | 8.30 | 9.92 | 0.1538 |
| 233.5084 | -1.96201 | 8.30 | 9.83 | 0.0787 |
| 1.2987 | 1.06057 | 8.24 | 9.82 | 0.1028 |
| 156.5582 | 48.74970 | 8.33 | 9.79 | 0.1604 |
| 226.0778 | 2.76445 | 8.17 | 9.65 | 0.0350 |
| 345.7720 | 1.24968 | 8.22 | 9.59 | 0.0690 |
| 168.1920 | 1.33819 | 8.17 | 9.49 | 0.1088 |
| 219.6623 | 53.14538 | 8.16 | 9.44 | 0.0900 |
| 197.1532 | 58.88513 | 8.16 | 9.41 | 0.1410 |

Notes. Sample of massive low-metallicity galaxies, reverse sorted by stellar mass. R.A. and decl. are in degrees (J2000.0), $12 + \log (O/\text{H})$ and stellar masses are from Tremonti et al. (2004).

§ Spiral galaxy.

### Table 2

Cuts for Sample Selection

| Cut | Number surviving |
|-----|------------------|
| Low magnitude errors | 86754 |
| 1% low O/H with respect to $M_*$ | 855 |
| 1% low O/H with respect to $M_*$ | 598 |
| 2.5% low O/H with respect to log $M_*$ | 381 |
| 2.5% high log $M_*$ with respect to O/H | 113 |
| Within 2σ of H II region of [O I] BPT diagram | 56 |
| OK spectrum reduction | 52 |
| Reproducible [N II]/Hα ratio | 44 |
| 2.5% low PP04 (O/H) with respect to log $M_*$ | 42 |

Notes. See Section 2 and Figure 3 for a more detailed explanation.
Figure 4. Baldwin, Phillips, & Terlevich diagrams of log([O III]/Hβ) vs. log([N II]/Hα) (left) and log([O III]/Hβ) vs. log([O I]/Hα) (right). Plotted are the spectroscopic galaxies from the SDSS DR4 (small gray points), the galaxies passing our luminosity, mass, and log(O/H) cuts but not in the final sample (open points), the galaxies passing the BPT diagram cuts (light gray points), and the galaxies in our final low-metallicity sample (dark gray points). Lines are taken from Kewley et al. (2006b).

Figure 5. Sample spectra. Two low-metallicity high-mass outliers (the top and middle panels) and one galaxy rejected as a potential AGN (bottom).

Figure 2 shows that 40 out of the 42 galaxies in our sample have disturbed morphologies suggestive of merging systems. Though some of the less-resolved galaxies in our sample may appear only slightly morphologically disturbed in the SDSS images, evidence suggests that, with higher resolution, these galaxies do in fact have unusual morphologies. In a Hubble Space Telescope study of local Lyman break galaxy (LBG) analogs, Overzier et al. (2008) found SDSSJ102613.97+4884458.9 ([α, δ] = 156.5580, 48.7497), leftmost image on the bottom row of Figure 2) to have a strongly asymmetric profile with several distinct knots of star formation. In a preliminary study of the most UV luminous galaxies, Hoopes et al. (2007) found that these high SSFR LBG analogs are metal-poor by ~ 0.5 dex relative to other galaxies of similar stellar mass. Hoopes et al. and Overzier et al. suggest that the observed high SSFRs and low metallicities for these LBG analogs are related to the galaxy...
collisions that formed these objects. (See also Struck et al. 2008 for a discussion of so-called delayed galaxies, i.e., high star-formation rate interacting galaxies which have apparently managed to retain most of their gas until $z = 0$.) In Section 3.2, we show how a simple merger-induced gas inflow picture can account for an offset in metallicity, and discuss possible shortcomings in this interpretation. The other two galaxies in the sample are undisturbed spiral galaxies. While these are clearly very interesting objects, we have no explanation to offer for their extreme offsets from the mass–metallicity relation.
3.1. Star-Formation Rates

Ellison et al. (2008a) have shown that galaxies with higher specific star-formation rates at a given mass have preferentially lower metallicities. In Figure 10, we plot the SSFR as a function of stellar mass for the SDSS star-forming galaxies. Most (but not all) of our low-metallicity outliers clearly have higher SSFRs than typical of the larger sample. We plot the SSFRs against the mass–metallicity residual from Tremonti et al. (2004) in Figure 11; generally speaking, aperture corrections for the SSFR only matter at the low SSFR end. While our low-metallicity outliers do have higher-than-normal SSFRs, this relative difference alone is not enough to explain their low oxygen abundances.

3.2. Observed Metallicity of Merging Galaxies

As seen in Figure 2, most of galaxies in this sample are tidally interacting. Simulations have shown that galaxy major mergers are accompanied by starbursts and gas inflow from large galactocentric radii (e.g., Barnes & Hernquist 1992; Mihos & Hernquist 1996; Cox et al. 2006). Because typical spiral galaxies have metallicity gradients (Kennicutt et al. 2003), the inflowing gas will have a lower oxygen abundance than the native central gas. This suggests that perhaps our galaxies’ observed low metallicities are a consequence of large quantities of low-metallicity gas from large galactocentric radii being transported into the central few kiloparsecs and diluting the metal-rich central gas.

We can test this idea at the order of magnitude level to verify that it can give the observed oxygen abundance offsets of $-0.3$ to $-0.8$ dex (see, e.g., Figure 7). The SDSS data measure the galaxies’ central oxygen abundances; we wish to know what the change in oxygen abundance would be if low-metallicity gas from larger radii were dumped into the central regions. If
we assume that all of the gas out to some large radius \( R \) was to participate in this inflow, then the lower abundance would be the same as if we simply measured the total oxygen abundance for the entire galaxy gas disk out to the radius \( R \). For reference, typical observed H I disks (e.g., Boomsma et al. 2008 in NGC 6946) have radii of \( R \sim 20 \) kpc. We consider a model spiral galaxy with a gradient of \( 12 + \log(O/H) \) of slope \( \Gamma_{O/H} \) in units of dex per kiloparsec; \( \Gamma_{O/H} \) is typically of order \(-0.05 \) dex kpc\(^{-1}\) (Zaritsky et al. 1994; van Zee et al. 1998; Kennicutt et al. 2003). We will also assume that our model galaxy has a gas surface density \( \Sigma \) that obeys a power-law relation with the radius such that \( \Sigma(R) = \Sigma_0 R^{-\alpha} \). While a constant surface density (\( \alpha = 0 \)) is a reasonable assumption at large radii (Wong & Blitz 2002; Leroy et al. 2008), we will show that the calculated oxygen abundance dilution is not strongly dependent on the choice of this power-law slope. For notational simplicity, in this section only we will use O/H as shorthand for the more cumbersome \( 12 + \log(O/H) \).

Let \( \langle O/H \rangle_{SDSS} \) be the mean O/H within an SDSS spectroscopic fiber of a spiral galaxy (i.e., within the central 3″ diameter). Formally,

\[
\langle O/H \rangle_{SDSS} = \frac{\int_0^{R_3} \Sigma(R) (O/H) R dR d\theta}{\int_0^{R_3} \Sigma(R) R dR d\theta},
\]

where \( R_3 \) is the radius in kiloparsec of the galaxy at a radius of 1.5″ (i.e., spanned by the 3″ SDSS fiber; this corresponds to \( \approx 4.9 \) kpc at \( z = 0.2 \)), and we are implicitly assuming the scale height of the galaxy is roughly constant with radius. For radii \( R > R_3 \), the oxygen abundance is \( O/H = (O/H)_0 + \Gamma_{O/H} R \), where \( (O/H)_0 \) is the oxygen abundance extrapolated to \( R = 0 \) using the adopted abundance gradient. We can now expand Equation (5) to find

\[
\langle O/H \rangle_{SDSS} = \left[ \frac{2 + \alpha}{2 \pi R_3^{2 \alpha} \Gamma_{O/H}} \right] \cdot 2\pi \int_0^{R_3} R^2 \{(O/H)_0 + \Gamma_{O/H} R\} R dR
\]

\[
= (O/H)_0 + \left[ \frac{2 + \alpha}{3 + \alpha} \right] \Gamma_{O/H} R_3.
\]

Solving for the \( R = 0 \) abundance, we find \( (O/H)_0 = (O/H)_{SDSS} - [(2 + \alpha)/(3 + \alpha)\] \( \Gamma_{O/H} R_3 \). The mean metallicity \( (O/H)_{< R} \) out to a radius \( R \) is therefore

\[
\langle O/H \rangle_{< R} = \frac{\int_0^R \Sigma(R) (O/H) R dR d\theta}{\int_0^R \Sigma(R) R dR d\theta}
\]

\[
= (O/H)_0 + \left[ \frac{2 + \alpha}{3 + \alpha} \right] \Gamma_{O/H} R.
\]

Hence, the change in metallicity \( \Delta(O/H) \) we would expect within an SDSS fiber diameter is \( \Delta(O/H) = [(2 + \alpha)/(3 + \alpha)] \Gamma_{O/H} \Delta R = [(2 + \alpha)/(3 + \alpha)] \Gamma_{O/H} (R - R_3) \). For an outer radius of \( R = 20 \) kpc, an inner radius of \( R_3 = 5 \) kpc, an abundance gradient of \( \Gamma_{O/H} = -0.05 \) dex kpc\(^{-1}\), and a flat radial gas surface density distribution of \( \alpha = 0 \), this leads to an oxygen abundance dilution of \( \Delta(O/H) = -0.5 \) dex, which is in the range we observe for these low-metallicity outliers (see, e.g., Figure 11).

We note that there are several caveats with this picture. First, we have assumed that the observed oxygen abundance corresponds to a mass-weighted abundance, whereas because we measure the metallicity via emission line spectra, it is actually weighted by the luminosities of the \( H\alpha \) regions. Secondly, it is unclear if the timescales involved pose any problem. Simulations show mergers do induce gas inflow to the centers of galaxies (Cox et al. 2006), but most of this inflow occurs during the first close encounter between the two galaxies. While a few of the galaxies in our sample do have nearby neighbors, most do not: SDSS detects only a single, if disturbed, galaxy. It is possible that these are not yet dynamically relaxed; the two galaxies can pass close enough to each other that they are seen by SDSS as one object. If a merger-induced starburst lasts \( \sim 1 \) Gyr (Cox et al. 2006), then \( \sim 1 \)% of all (properly defined) starburst mergers should display lower-than-expected metallicities. The relevant dynamical timescale for gas inflow depends on the typical radius from which the gas originates. Because the dynamical time \( t_{dynam} \approx R/v_{esc} \), gas at larger radii takes longer to reach \( R_3 \) and help dilute the central metallicity.

Several studies have shown that galaxies in close pairs tend to have lower metallicities than expected. Kewley et al. (2006a) found that galaxies separated by \( \lesssim 20 h^{-1} \) kpc have systematically lower oxygen abundances by \( \sim 0.2 \) dex. On the other hand, Ellison et al. (2008b) found an offset of \( \sim 0.05 \) dex in \( 12 + \log(O/H) \) at fixed mass galaxies in pairs with similar separations; the investigations of Michel-Dansac et al. (2008) of galaxies in close pairs suggest that the relative log(O/H) offset is greater for the lower-mass galaxy in the pair than for the higher-mass galaxy. Kewley et al. also found relatively high SSFRs for the lower-metallicity member in their galaxy pairs; they attribute both the starburst activity and the lower oxygen abundance to fresh gas inflowing to the galaxies’ central regions due to interaction with the closely neighboring galaxy.

In a similar vein, Lee et al. (2004) found that morphologically disturbed galaxies have systematically lower oxygen abundances (or higher luminosities) than galaxies of similar brightness (or metallicity). Likewise, luminous infrared galaxies (LIRGs), whose high SSFRs and highly disturbed morphologies are believed to be due to a recent major merger, are observed to have oxygen abundances that are \( \sim 0.4 \) dex lower than other galaxies of comparable masses (Rupke et al. 2008). The pronounced blue colors of our outliers (see Figure 9) imply that while the star-formation rates for many of these galaxies are consistent with those of LIRGs, these outliers are clearly not as dusty as their infrared-luminous cousins; it is unclear the extent to which these classes of galaxies are related, and why, if LIRGs do typically have such relatively low metallicities, no galaxies in our sample are extremely red.

4. CONCLUSIONS AND IMPLICATIONS

We have identified a sample of 42 low-metallicity high-mass outliers from the mass–metallicity relation. As a population, these galaxies have disturbed morphologies and high SSFRs, implying that they are undergoing a merger-induced starburst. We propose that their observed low oxygen abundances are due the tidal interaction inducing large-scale gas inflow which subsequently dilutes the central interstellar medium in these galaxies. While there have been several observational and theoretical suggestions that interacting galaxies will result in a decreased observed gas-phase metallicity, this is the first work that has shown that the vast majority of severe low-metallicity outliers from the mass–metallicity relation are morphologically disturbed. Finally, we note that the cuts outlined in Section 2.1 provide an effective means of using only colors and spectra to identify a rather pure (though not necessarily complete) sample of tidally disturbed galaxies.
One striking implication of these results is that, while it is safe to assume that the metallicities for populations of galaxies will fall within a particular range of values given their luminosities at redshifts for which the luminosity–metallicity relation has been measured, one should not assign metallicities to individual galaxies based solely on their luminosities. For example, while studies of the host galaxies of long gamma-ray bursts (GRBs) suggest that GRBs are only found in low-metallicity environments (Stanek et al. 2006; Kewley et al. 2007), several recent GRBs have been associated with very luminous hosts, such as GRB 070306 and its $M_B \sim -22.3$ host galaxy (Jaunsen et al. 2008). As shown in this paper and Paper I, assuming an oxygen abundance for a galaxy from its luminosity alone can result in mis-estimating 12 + log(O/H) in luminous galaxies by a whole dex, and thus one should not assume, e.g., the host of GRB 070306 necessarily has a high metallicity. For cases in which log(O/H) has been measured via emission line spectra for GRB hosts, it is generally low, even if the galaxy is luminous. For example, the host galaxy of GRB 031203 has an absolute $B$-band magnitude similar to that of the Milky Way, yet Margutti et al. (2007) find it to have a low metallicity ($12 + \log (\text{O/H}) = 8.12$) as well as a high star-formation rate ($\sim 13 M_\odot$ yr$^{-1}$). Prochaska et al. (2004) interpret this offset in metallicity as a sign that GRB 031203 went off in a “very young star-forming region,” which is in line with our interpretation in Section 3.2. Furthermore, the brighter GRB hosts studied by Fruchter et al. (2006) are morphologically very similar to our massive low-metallicity galaxies, and our results strongly suggest that the oxygen abundances inferred from luminosity alone are uncertain by as much as 1 dex. Specifically, if a luminous galaxy is morphologically disturbed, has a high SSFR, and is extremely blue, then it should not be assumed to lie within the luminosity–metallicity locus of star-forming galaxies.

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