A POPULATION OF METAL-POOR GALAXIES WITH \( \sim L^* \) LUMINOSITIES AT INTERMEDIATE REDSHIFTS

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ABSTRACT

We present new spectroscopy and metallicity estimates for a sample of 15 star-forming galaxies with redshifts in the range 0.29–0.42. These objects were selected in the KPNO International Spectroscopic Survey via their strong emission lines seen in red objective-prism spectra. Originally thought to be intermediate-redshift Seyfert 2 galaxies, our new spectroscopy in the far red has revealed these objects to be metal-poor star-forming galaxies. These galaxies follow a luminosity–metallicity \((L-Z)\) relation that parallels the one defined by low-redshift galaxies, but is offset by a factor of more than 10 to lower abundances. The amount of chemical and/or luminosity evolution required to place these galaxies on the local \(L-Z\) relation is extreme, suggesting that these galaxies are in a very special stage of their evolution. They may be late-forming massive systems, which would challenge the current paradigm of galaxy formation. Alternatively, they may represent intense starbursts in dwarf–dwarf mergers or a major infall episode of pristine gas into a pre-existing galaxy. In any case, these objects represent an extreme stage of galaxy evolution taking place at relatively low redshift.

Key words: galaxies: abundances – galaxies: starburst

1. INTRODUCTION

It has recently become possible to obtain metallicity estimates for galaxies with significant look-back times. While nearly all precision studies of galaxian abundances carried out before 2000 focused on nearby objects \((z < 0.1)\), recent emphasis on deep, high-redshift surveys has opened the way to studying chemical evolution out to \(z = 1\) and beyond (Lilly et al. 2003; Kobulnicky et al. 2003; Liang et al. 2004; Maier et al. 2004, 2005, 2006; Shapley et al. 2005; Lamareille et al. 2006; Erb et al. 2006, Kakazu et al. 2007; Liu et al. 2008; Maiolino et al. 2008; Rodrigues et al. 2008). It is now possible to utilize measurements of the chemical evolution of galaxies (e.g., via the redshift dependence of the mass–metallicity or luminosity–metallicity \((L-Z)\) relation) as an important tool for understanding galaxian evolution in general. Any model/scenario for the formation and evolution of galaxies must account for the \(L-Z\) relation and its change as a function of redshift.

Advances in our knowledge of galaxian metal abundances have also occurred among low-redshift samples. The seminal paper by Tremonti et al. (2004) using the Sloan Digital Sky Survey (SDSS; York et al. 2000; Adelman-McCarthy et al. 2008) provided \(L-Z\) and mass–metallicity relations for \(\sim 53,000\) SDSS galaxies. On a smaller scale, Salzer et al. (2005b) utilized the spectra for 765 star-forming galaxies from the KPNO International Spectroscopic Survey (KISS) to create optical and NIR \(L-Z\) relations. The availability of reliable local \(L-Z\) relations, based on large, homogeneous samples, has been essential for establishing a baseline for comparing with high redshift samples. Much work continues with these low-\(z\) samples in order to better quantify the shape of the \(L-Z\) relation, as well as to improve the calibration of the metallicity scale at the high-abundance end.

The amount of metallicity evolution occurring between \(z\) of 0.5–1.0 and today inferred from the studies mentioned above is small. This was generally expected, and is consistent with the picture that the bulk of galaxy assembly took place prior to \(z = 1\). For example, Lilly et al. (2003) found that only a \(\sim 20\%\) change in \(O/H\) relative to galaxies at \(z = 0\) is required to explain the observed metallicities in their sample at a mean redshift of 0.75. Other studies (e.g., Maier et al. 2004; Liang et al. 2004, Lamareille et al. 2006) infer a larger amount of metallicity evolution, but in nearly all cases no more than a factor of 2 for galaxies between \(z = 1\) and today. Moreover, our recent observations of KISS galaxies at intermediate redshifts \((z \approx 0.29-0.42)\) have revealed that the overall picture may not be as simple as previously believed. The current Letter presents new results that indicate the presence of a population of very metal-poor yet luminous galaxies at modest look-back times of 3–4 Gyr.

2. HIGHER-\(Z\) KISS GALAXIES

The KISS galaxy sample is derived from a wide-field Schmidt survey that selects emission-line objects via the presence of \(H\alpha\) emission in their objective-prism spectra (Salzer et al. 2000, 2001; Gronwall et al. 2004b). The survey method included using a filter that restricted the wavelength coverage of the slitless spectra to 6400–7200 Å. KISS detects objects via their \(H\alpha\) emission out to \(z = 0.095\). However, follow-up spectroscopy of KISS objects (Wegner et al. 2003; Gronwall et al. 2004a; Jangren et al. 2005; Salzer et al. 2005a) revealed that \(\sim 2\%\) of the overall sample were not detected by \(H\alpha\) emission but instead were higher-redshift objects with [O \(\text{iii}\)] \(\lambda 5007\) shifted into the bandpass of the survey filter. These objects have \(z\) between 0.29 and 0.42. Virtually all of the 38 [O \(\text{iii}\)]-selected objects exhibited high-excitation spectra ([O \(\text{iii}\)]/H\(\beta\) \(> 3\)), and most had M\(_{\text{B}}\) between \(-19.5\) and \(-22.5\). The combination of high-excitation spectra and high luminosities caused us to classify them initially as Seyfert 2 galaxies, based solely on their blue rest frame spectra (e.g., see Figure 4 of Gronwall et al. 2004a).

The activity type of an emission-line galaxy (e.g., AGN versus star forming) cannot be unambiguously determined using a single flux ratio such as [O \(\text{iii}\)]/H\(\beta\). The redshifts of the [O \(\text{iii}\)]-selected KISS galaxies meant that the key diagnostic line ratio [N \(\text{ii}\)]/H\(\alpha\) was nearly always beyond the red end.
of our quick-look follow-up spectra. In order to resolve the ambiguity regarding their type classifications, we undertook a program of spectroscopy in the far red (6300–9500 Å) that allowed us to observe the important lines around Hα. All observations for this program were obtained using the 9.2 m Hobby–Eberly Telescope4 (HET). Figure 1 shows spectra of three KISS galaxies observed with the HET. The details of the observations will be presented in A. L. Williams, J. J. Salzer, & C. Gronwall (2009, in preparation).

The results of the red spectroscopy were surprising. As expected, many of the [O iii]-selected KISS galaxies (23 of the 38, or 61%) were bona fide AGNs—mostly Seyfert 2s. However, 15 (39%) exhibited low [N ii]/Hα ratios, indicative of gas that is photoionized by hot stars. The three spectra illustrated in Figure 1 are all examples of the latter. Figure 2 shows the line ratio diagnostic diagram for the [O iii]-selected objects. The Seyfert 2’s are located in the expected region of the diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). The star-forming subset of the high-z KISS galaxies are located in the upper left portion of the diagram, in the area occupied by metal-poor star-forming dwarf galaxies (aka blue compact dwarfs (BCDs)). In other words, the star-forming galaxies detected via their strong [O iii] emission appear to have spectra similar to low-metallicity dwarf galaxies, despite having luminosities comparable to L*.

4 Based on observations obtained with the Hobby–Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and the Georg-August-Universität Göttingen.
3. LOW-METALLICITY STAR-FORMING GALAXIES

We estimate the oxygen abundances of the [O III]-selected star-forming galaxies using the “coarse abundance” method described in Melbourne & Salzer (2002) and Salzer et al. (2005b). This method utilizes ratios of strong lines ([O III]λ5007/Hβ, [N II]λ6583/Hα) present in the spectra to infer the abundance, based on an empirical calibration between the ratios and metal abundances for objects of known metallicity. While more accurate estimates are possible for many of the higher-z KISS galaxies, we employ the coarse method here to be consistent with the method used to estimate the abundances of the comparison sample of low-z KISS galaxies. As emphasized by Kewley & Ellison (2008), it is essential to use a consistent metallicity calibration when comparing different L–Z relations. The uncertainty in the O/H values derived in this way is 0.15–0.20 dex (Salzer et al. 2005b). Key properties of the [O III]-selected KISS galaxies, including their luminosities and abundance estimates, are given in Table 1. The B-band absolute magnitudes were derived using the V-band photometry published as part of KISS (e.g., Salzer et al. 2001), since V is fairly close to rest frame B for the redshifts of interest. All KISS photometry is on the Vega system. A small incremental K-correction was then applied using the observed color and precise redshift of each KISS galaxy. Note that two of the galaxies in the sample exhibit spectra with signal-to-noise ratios too low to provide a reliable abundance estimate. These galaxies are not included in the following discussion.

Figure 3 presents an L–Z diagram for the 13 [O III]-selected star-forming galaxies. Also plotted are 1363 low-z KISS galaxies (⟨z⟩ = 0.058, z range = 0.0 to 0.095) with metallicity estimates derived in an identical way. The upper solid line is a bivariate linear fit to the low-z galaxies, while the lower dashed line has the same slope but is offset to provide the best fit to the higher z objects. The fit to the [O III]-selected galaxies is offset by ∼1.1 dex to lower abundances (factor of 13) relative to the low-z sample. This is an amazing result, since it implies that up to a factor of 13 increase in the metallicity of these galaxies is required between a redshift of 0.29–0.42 and today (a look-back time of 3–4 Gyr, where we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M$ = 0.27, and $\Omega_\Lambda = 0.73$). A key point to stress is that none of the galaxy samples referred to above with redshifts out to $z = 1$ and beyond exhibit such a large metallicity offset. Most would be no more than a factor of 2 below the local L–Z relation (0.3 dex), despite having much larger look-back times. It is worth noting that the large metallicity offset seen in Figure 3 between the two samples is present regardless of which abundance calibration used by Salzer et al. (2005b) is adopted.

As mentioned above, the spectra of the [O III]-selected star-forming galaxies closely resemble those of low-redshift BCDs. The lower two spectra presented in Figure 1 are particularly good examples of this fact. It is tempting to interpret their locations in the L–Z diagram as being due to an extreme luminosity enhancement due to a starburst in a dwarf galaxy. If the offset of the [O III]-selected galaxies from the mean trend defined by the low-z KISS galaxies is assumed to all be due to an increase in their luminosity, it would require an increase of 3.6 magnitudes (factor of ∼28)! For BCDs in the local universe, the luminosity enhancement from their current starburst is more typically a factor of 2 above the luminosity of the quiescent host galaxy (e.g., Salzer & Norton 1999; Lee et al. 2004). A more plausible interpretation would be that the high-z KISS galaxies are both metal-poor and overluminous relative to local star-forming galaxies. If we assume a factor of 2 luminosity enhancement due to the starburst (0.75 mag), then the implied offset in metallicity from the local sample is ∼0.9 dex, or a factor of ∼8. This is still a factor of 4 below the L–Z relations of the $z \sim 1$ galaxies referred to above.

4. DISCUSSION

The discovery of a population of low-abundance galaxies with ∼L* luminosities at intermediate redshifts raises two fundamental questions. First, why have these types of objects not been discovered previously? Second, what is the nature of these enigmatic objects?

4.1. A New Class of Galaxy?

Given the large number of studies of metal abundances in galaxies with intermediate and high redshift mentioned in the Introduction, it may seem odd that systems similar to
those described here have not been recognized previously. Our interpretation of this enigma centers on the fact that the [O III]-selected low-metallicity KISS galaxies are likely to be quite rare. Over the 136.1 deg$^2$ covered by KISS lists included in this study, only 15 such objects were detected. Hence, the probability of finding an analog to one of these systems in a deep pencil-beam survey (e.g., GEMS, Giavalisco et al. 2004; GOODS, Rix et al. 2004, etc.) that tends to cover a small fraction of a square degree is small. Furthermore, the typical apparent magnitude of these sources is $B \sim 20–22$, making them fainter than the spectroscopic limits of wide-field surveys like SDSS.

The selection method of KISS favors the detection of objects with strong, high-equivalent-width emission lines. Even objects with no detectable continuum (and hence very faint apparent magnitudes) can be detected in KISS if their emission lines are of sufficient strength. Interestingly, the types of objects described here are probably the only type of star-forming galaxy that KISS could be sensitive to at these redshifts. Metal-rich star-forming systems would have [O III] lines that are too weak for detection, while strong-lined dwarfs would likely be too faint. Only this type of $\sim L^*$ galaxy with low metal abundances and hence strong [O III] lines could be detected by KISS in this redshift range.

We do not wish to imply that the objects described here are unique. Rather, they have largely been missed by previous studies. Even so, there are examples of similar galaxies in the literature. For example, the study of Maier et al. (2004) includes one object in their $z \approx 0.4$ sample that is well below the $L-Z$ trend defined by the rest of the sample. More recently, Kakazu et al. (2007) used a narrowband selection process to select strong emission-line galaxies via the [O III] line at $z = 0.63$ and 0.83. Several of their objects fall well below the local $L-Z$ relation, and may be examples of the type of galaxy we are describing here.

Another sample of galaxies that appear to bear some resemblance to the [O III]-selected KISS galaxies are the so-called local Lyman Break analogs studied recently by Hoopes et al. (2007) and Overzier et al. (2008). These objects are selected primarily on their UV properties, and have redshifts from 0.1 to 0.3. While these objects have been found to be slightly metal-poor compared to normal galaxies of the same mass (by roughly a factor of 2 for galaxies in the luminosity range covered by the KISS sample), they are not as extreme as the [O III]-selected KISS galaxies. Additional study will be needed to determine whether the two samples are drawn from the same population of galaxies.

A lower limit to the volume density of this class of galaxy is $4.3 \times 10^{-7}$ Mpc$^{-3}$, obtained by dividing our 15 detections by the effective volume of the KISS survey in the $z = 0.29–0.42$ range. This assumes that all of the detected sources would be visible throughout this volume. In reality, the actual density is likely to be somewhat higher, but the small sample size makes deriving a more accurate effective volume dubious. To compare our density estimate with that of the overall galaxy population at this redshift, we utilize the luminosity function derived by Faber et al. (2008) for galaxies in the redshift range 0.2–0.4. Integrating over absolute magnitudes of $M_B = -19.8$ to $-21.8$, we obtain an overall volume density of $2.5 \times 10^{-3}$ Mpc$^{-3}$. Hence, the [O III]-selected low-metallicity KISS galaxies appear to make up only a tiny fraction of the galaxy population in this redshift range.

In the Kakazu et al. (2007) study mentioned above, their [O III]-selected samples at $z = 0.63$ and $z = 0.83$ both have volume densities of order $10^{-3}$ Mpc$^{-3}$. When compared to the much smaller value found for the KISS [O III]-detected sample, this suggests the possibility that strong-lined [O III] emitters were more common at earlier epochs. However, given the different sensitivity limits of the two samples, plus the likelihood that the overall properties of the two sets of galaxies are vastly different, one should interpret this result with caution.

### 4.2. Evolutionary Scenarios

What exactly do these luminous but metal-poor galaxies represent? One possibility is that they are “straggler” galaxies, essentially the last group of massive objects to collapse and form stars. In this case, their low abundances are due to their relatively young ages. While the current paradigm of galaxy formation calls for most massive systems to begin their collapse and subsequent star formation at a much earlier epoch, we cannot rule out the possibility of late-forming galaxies. In this scenario, the progenitor gas clouds initially would have resisted gravitational collapse, perhaps due to a low overall gas density. Subsequent evolution of the system might have been inhibited until a specific event occurred to raise the density sufficiently for collapse to occur. Potential triggers could include cloud–cloud collisions or tidal interactions with a passing galaxy. Such a scenario would likely demand that the progenitor system resides in a fairly low-density region. Future studies of the local environments of the [O III]-selected KISS galaxies would likely yield interesting results. Since metallicity enrichment can occur fairly quickly in massive galaxies, there would be sufficient time in the intervening 3–4 Gyr for the abundances to increase, such that these galaxies would no longer stand out as being metal poor in the local universe.

Alternatively, these objects may represent extreme starbursts in otherwise fairly normal dwarf galaxies. In this case, the low metallicities are simply the norm for the class. Their locations in the $L-Z$ diagram would be due to a large brightening due to a massive starburst. We showed in Section 3 that the luminosity enhancement needed to explain these objects is a factor of $\sim 28$. This would only be possible in the case of an unusually severe dwarf–dwarf merger. However, this amount of luminosity enhancement seems extreme! In the local universe the typical brightening due to a starburst in a BCD (the systems with the highest relative starburst strengths) is only a factor of 2–3 in most cases (Salzer & Norton 1999).

Another way to explain these systems would be the accretion of large amounts of pristine gas by $L^*$ galaxies that start out with fairly normal metallicities. However, this scenario would require that the mass of accreted gas be roughly a factor of 10 larger than the mass of the original ISM in order to dilute the gas phase abundances to the observed levels. Again, the likelihood of this happening seems low, but it cannot be ruled out.

Regardless of the case, these are extremely interesting systems. The fact that none are observed in the local universe indicates that rapid evolution of the systems is required. Presumably, we are witnessing a short-lived episode in the life of these objects, one in which they are going through an extreme phase in their evolution. Whether or not this is a normal process that all galaxies go through at some point remains to be determined. There is a distinct possibility that these objects are going through an evolutionary stage that is common to most galaxies, albeit at an earlier epoch. If true, the study of these galaxies will allow us to probe a critical phase in galaxy evolution using systems that are much closer than their high-redshift counterparts.
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