CLUES TO THE ORIGIN OF THE MASS-METALLICITY RELATION: DEPENDENCE ON STAR FORMATION RATE AND GALAXY SIZE

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ABSTRACT

We use a sample of 43,690 galaxies selected from the Sloan Digital Sky Survey Data Release 4 to study the systematic effects of specific star formation rate (SSFR) and galaxy size (as measured by the half-light radius, $r_h$) on the mass-metallicity relation. We find that galaxies with high SSFR or large $r_h$ for their stellar mass have systematically lower gas-phase metallicities (by up to 0.2 dex) than galaxies with low SSFR or small $r_h$. We discuss possible origins for these dependencies, including galactic winds/outflows, abundance gradients, environment, and star formation rate efficiencies.

Subject headings: galaxies: abundances — galaxies: ISM

1. INTRODUCTION

The well-established luminosity-metallicity relation (LZR) that exists over at least 10 mag in $M_B$ (e.g., Skillman et al. 1989; Zaritsky et al. 1994; Salzer et al. 2005; Lee et al. 2006a) has been recently confirmed to be a manifestation of a more fundamental stellar mass-metallicity relation (MZR; Lequeux et al. 1979; Tremonti et al. 2004). Although there is evidence that galaxy interactions may affect the normalization of the LZR and MZR (Kewley et al. 2006; Ellison et al. 2007; Rupke et al. 2007), the MZR appears to be independent of large-scale environment (Mouhcine et al. 2007) and remains intact out to $z \sim 2.5$ (Savaglio et al. 2005; Erb et al. 2006).

Several origins of this apparently fundamental relation have been proposed. Many of these models invoke winds as the fundamental driver of the MZR (e.g., Kobayashi et al. 2007) and observational evidence indicates that gas ejection and/or accretion could be important (Tremonti et al. 2004; Gallazzi et al. 2005). However, the effects of supernova feedback on star formation efficiency and metal-poor gas infall have also been cited as important factors (Brooks et al. 2007; Finkelator & Davé 2007). In this Letter, we investigate the dependence of the MZR on various physical parameters that may shed light on the underlying mechanism that shapes it.

We adopt a concordance cosmology of $\Omega_M = 0.7$, $\Omega_{\Lambda} = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc where applicable.

2. DATA SAMPLE

We use the Sloan Digital Sky Survey Data Release 4 (SDSS DR4) to compile a sample of star-forming galaxies with spectra suitable for metallicity determinations. The galaxy sample is very similar to the “control” sample used in the study of close galaxy pairs by Ellison et al. (2007) where a full description of the sample selection is presented. In brief, the sample consists of galaxies with extinction-corrected Petrosian magnitudes in the range 14.5 $< r < 17.77$ with strong emission lines. Galaxies must be classified as star-forming and not AGN-dominated, according to the line diagnostic criteria given in Kewley et al. (2001). The galaxies must also have available metallicities from the Kewley & Dopita (2002) “recommended” method, masses determined from spectral synthesis modeling (Kauffmann et al. 2003b), aperture-corrected SFRs from Brinchmann et al. (2004), and photometric/morphological parameters such as $r$-band half-light radii ($r_h$) and bulge-to-total fractions ($B/T$) from L. Simard (in preparation) derived from GIM2D (see Simard et al. 2002 for details on the fitting procedure). The GIM2D $r_h$ values are in excellent agreement with the values derived from Sérsic fits (Blanton et al. 2005). In contrast to Ellison et al. (2007), we do not impose an upper redshift limit and we require the fiber covering fraction (CF: the ratio of the $g$-band Petrosian to fiber fluxes) to be CF $\geq 20\%$ in order to minimize the aperture effects on metallicity (e.g., Kewley et al. 2005; Ellison & Kewley 2006; Kewley & Ellison 2007). The final sample consists of 43,690 galaxies with a median redshift of $z = 0.086$.

3. RESULTS

In Figure 1 we show the MZR for our sample of $\sim$44,000 SDSS galaxies divided by specific star formation rate (SSFR). For reference, the median $H_0 + [N II]$ equivalent width (EW), which is a measure of the present to past-average star formation rate (see Fig. 3 of Kennicutt et al. 1994), of galaxies with log SSFR $> -9.5$ is 56 Å. Since SSFR itself depends on mass, with lower values at higher masses, we plot the SSFRs by tertiles calculated separately in each mass bin. At high stellar masses ($log M_*/M_{\odot} > 10 M_{\odot}$) the MZR exhibits no dependence on SSFR. At lower stellar masses, there is a tendency for galaxies with higher SSFR to have lower metallicities for a given stellar mass. The offset in metallicity from the highest to lowest SSFR bin is $\sim$0.10–0.15 dex in the stellar mass range $9 M_{\odot} < log M_*/M_{\odot} < 10 M_{\odot}$ and is significant at greater than 5 $\sigma$ (the standard error on the mean) in these mass bins.

In Figure 2 we again show the MZR for our sample of SDSS galaxies, but now divided by half-light radius. Since $r_h$ itself depends on mass, with a tendency toward higher values at higher masses, we plot the $r_h$ by tertiles calculated separately in each mass bin. There is an offset in metallicity between the...
galaxies with the smallest optical extents and those with the largest half-light radii, with a range in the binned values of between 0.05 and 0.2 dex. A similar result was noted by Tremonti et al. (2004), who found that, for a fixed $M_*$, galaxies with higher mass surface density (i.e., smaller $r_h$) had higher metallicities, equivalent to the trend in Figure 2. The significance of the metallicity offset between $r_h$ tertiles in the range $9 < M_*/10 M_*$ is greater than 10 $\sigma$ in a given mass bin. However, despite the offsets shown in Figures 1 and 2, the dependence of the MZR on SSFR and $r_h$ is not a significant cause of scatter in the relation as a whole (i.e., when all galaxies are included). The decrease in scatter for the MZR binned by $r_h$ compared to the full sample is less than 10%, indicating that the scatter is dominated by either an additional parameter, observational errors, or the accuracy of the metallicity calibration. As was the case for the offsets in SSFR, in the stellar mass bins with sufficient statistics, we see a tendency for larger offsets in the MZR between $r_h$ bins at lower stellar masses. The offset in the MZR when binned by $r_h$ is not due to a correlation between size and morphology. Figure 3 shows that the MZR is not significantly different for galaxies with different bulge fractions.

Trends in the MZR with size have previously been reported in the literature, e.g., Hoopes et al. (2007) for local UV luminous galaxies and Ellison et al. (2007) for galaxies with close companions. However, both of these studies have found that more compact galaxies have lower metallicities for their mass, compared with more extended galaxies. This trend is opposite to what we see in Figure 2. One explanation is that the MZR offsets seen by Hoopes et al. (2007) and Ellison et al. (2007) are the result of merger-induced activity, as supported by the MZR offsets observed in luminous and ultraluminous infrared galaxies by Rupke et al. (2007). We discuss alternative origins for the trends in Figures 1 and 2 in the next section.

Before discussing the possible physical origin of the MZR’s dependence on SSFR and $r_h$, it is interesting to consider the practical impact of these dependences on comparisons between local and high-redshift versions of the MZR. Once aperture effects and the use of a single metallicity diagnostic (e.g., Ellison & Kewley 2006; Kewley et al. 2005; Savaglio et al. 2005; Erb et al. 2006; Kewley & Ellison 2007) are accounted for, there is an offset to lower metallicities by about 0.3 dex for a galaxy of given mass at $z \sim 2.5$ compared with $z = 0$ (Erb et al. 2006). However, our results indicate that the observational selection biases of Lyman break galaxy (LBG) samples may also play a role. Due to the $(1 + z)^4$ surface brightness dimming effect, it is easier to detect and study high-redshift galaxies when they are compact. The typical $r_h$ of a redshift break LBG is $\sim 2 h_{70}^{-1}$ kpc (Dickinson 2000), which could potentially result in an upward shift in their observed MZR (see Fig. 2). Conversely, LBGs tend to have quite high SSFRs; all of the binned SSFRs in Erb et al. (2006) have values of log SSFR $\geq -9.3$ yr$^{-1}$, which would result in a downward shift in their MZR (see Fig. 1) relative to a more complete local sample. To assess the combination of these opposite trends, we compare the MZR
of our full sample of 43,690 galaxies with that of the 473 galaxies with \( r_g \leq 2 h_70^{-1} \) kpc and SSFR \( \geq 9.3 \) yr \(^{-1} \) (the “LBG-like” sample). We find that the LBG-like sample has a small negative offset, i.e., to lower metallicities, by \( \sim 0.05 \) dex at stellar masses \( \log M_\star < 10 M_\odot \); the effect of SSFRs therefore appears to dominate in this regime. For stellar masses \( M_\star > 10^2 M_\odot \), where the MZR is independent of SSFR (see Fig. 1), the effect of the \( r_g \) dependence is dominant and the MZR of the LBG-like galaxies is positively offset by \( \sim 0.05 \) dex, as expected from Figure 2. However, these shifts are much smaller than the observational scatter in either the low- or high-redshift MZR.

4. DISCUSSION: POSSIBLE INTERPRETATIONS OF MASS-METALLICITY TRENDS

Abundance gradients.—Radial gradients in galactic oxygen abundance are well established and have typical magnitudes of \( -0.01 \) to \( -0.05 \) dex kpc\(^{-1} \) (i.e., higher metallicities in the centers of galaxies), with \( -0.03 \) dex kpc\(^{-1} \) typical for local spiral galaxies (e.g., Zaritsky et al. 1994). A combination of fiber covering fraction and abundance gradient effects could therefore cause an apparent dependence of the MZR on \( r_g \). The median CFs are 0.40, 0.29, and 0.24 for the smallest, intermediate, and largest \( r_g \) tertiles, respectively, at \( \log M_\star = 10 M_\odot \). For a fixed abundance gradient, galaxies with higher fiber covering fractions are expected to have lower observed metallicities, since the fiber probes more of the outer disk. Hence, an aperture bias would lead to lower metallicities in small \( r_g \) galaxies (whose CF is large), opposite to what we find in Figure 2. However, if the steepness of abundance gradients depends on \( r_g \) for a given mass, then aperture effects may play a role. The dependence of radial abundance gradients is complex and may depend on morphology (such as the presence of a bar; e.g., Martin & Roy 1995), as well as size and galactocentric radius (Magrini et al. 2007). It is also not clear how the magnitude of an abundance gradient varies with \( r_g \). On the one hand, nearby dwarfs tend to have very flat abundance gradients (e.g., Lee et al. 2006b). Conversely, Prantzos & Boissier (2000) have shown that spiral galaxies with smaller disks may have steeper gradients than those with large disks.

Nonetheless, we can still consider whether the typical differences in abundance gradients between galaxies of different sizes could yield offsets in the MZR commensurate with the observed segregation in Figure 2. At the median redshift of our sample, the SDSS fiber radius corresponds to \( \sim 2 h_70^{-1} \) kpc and the typical abundance offset between large and small \( r_g \) galaxies in Figure 2 is 0.1–0.2 dex. Since the difference between the abundance gradients of large disks and either small disks or dwarfs is small, typically \( \ll 0.05 \) dex kpc\(^{-1} \), these differences seem unlikely to be the cause of the offsets in Figure 2. We can also test empirically for the effect of varying abundance gradients by looking for segregation in the MZR based on both cuts in \( r_g \) and covering fraction, where the presence of \( r_g \)-dependent gradients plus aperture effects would manifest themselves as a smaller segregation by \( r_g \) as the covering fraction increased. We find no evidence for such an effect (although the median CF of our sample is only 30%). We conclude that abundance gradients are unlikely to explain (all) of the \( r_g \) dependence seen in Figure 2.

Galactic winds.—Winds may seem like a natural explanation for the dependence of the MZR on \( r_g \) and SSFR. For example, the results shown in Figure 1 could be explained by a wind model in which higher SSFRs lead to more efficient evacuation of metals and hence a downward shift in the MZR. However, this explanation requires an assumption of instantaneous mixing of metals into the cool interstellar medium (ISM). In reality, the metals produced in the current episodes of star formation (i.e., those measured by the SSFR) have not yet sufficiently cooled to be traced by the H II phase. Moreover, while galaxies with smaller \( r_g \) for a given \( M_\star \) will have more centrally concentrated stellar masses and higher surface gravities, in the models of Finlator & Davé (2007) the wind velocities are always easily high enough to escape the potential wells of the galaxies’ gravity. If true in practice, this would indicate that gravitational potential alone is not sufficient to inhibit metal loss through winds in more centrally concentrated galaxies. An alternative is that the hot wind entrains more of the cool ambient ISM. However, Dalcanton (2007) has used an analytic model of gas inflow/outflow to show that even a modest amount of star formation following metal loss through winds quickly erases the signature of such an event.

Infall of metal-poor gas.—In the model of Finlator & Davé (2007), it is proposed that all galaxies have a fundamental equilibrium metallicity \( (Z_{eq}) \) for a given mass. Deviations from this value are caused by the inflow of pristine gas from the IGM, but \( Z_{eq} \) is eventually restored by the effects of star formation, winds, and mass loss. In this scenario, the low metallicities seen in Figure 1 could be explained by recent inflow of metal-poor gas which shifts the MZR from its equilibrium position. In response to the deposition of fresh fuel, which in turn increases the gas surface density, the galaxy will experience an increase in its SFR. Indeed, the same qualitative dependence of the MZR on SSFR is seen in the models (K. Finlator 2007, private communication). The dependence on SSFR is more pronounced at lower masses since it is more difficult to perturb a high-mass galaxy from its equilibrium position.

On the other hand, the timescale arguments of the infall model appear inconsistent with Figure 2. The time taken to recover from the injection of metal-poor gas and return to the equilibrium metallicity is the dilution time, \( t_D = M_{gas}/\dot{M}_{acc} \), where \( M_{gas} \) is the gas mass and \( \dot{M}_{acc} \) is the gas accretion rate. If \( t_D < t_{dyn} \) (where \( t_{dyn} \) is the dynamical time) then the galaxy “recovers” its equilibrium metallicity promptly, leading to very little scatter in the MZR. Conversely, if \( t_D > t_{dyn} \), then the galaxy struggles to recover promptly from inflows, leading to a large scatter in the MZR, due to galaxies which are displaced to lower metallicities. Since \( t_{dyn} \propto r^{-1/2} \), then, all other things being equal, \( t_D/t_{dyn} \propto r^{3/2} \). Therefore, galaxies with smaller radius may be expected to have larger \( t_D/t_{dyn} \), hence taking longer to recover their equilibrium metallicity after an injection of metal-poor gas. This effect should manifest itself in Figure 2 as a shift toward lower metallicities for smaller \( r_g \) galaxies if a large fraction of them have experienced recent infall. Indeed, such an effect is seen in the galaxy pairs sample of Ellison et al. (2007). However, the inverse of the expected \( r_g \) dependence is seen in the galaxy sample considered here, with small \( r_g \) galaxies exhibiting the highest metallicities for a given mass.

Environmental dependence.—This also seems an unlikely explanation for the trends in Figures 1 and 2. Mouhcine et al. (2007) have recently shown that the MZR does not depend sensitively on large-scale environment. While galaxy interactions can perturb the LZR and MZR (Kewley et al. 2006; Rupke et al. 2007), the dependence of this effect on \( r_g \) is the opposite to that seen in Figure 2 (Ellison et al. 2007). Moreover, Ellison et al. (2007) attributed the \( r_g \) dependence of the MZR in galaxy pairs to the stabilizing effect of a bulge (e.g., Mihos & Hern-
quint 1994, 1996; Cox et al. 2007). We find that there is no significant difference in the MZR for galaxies with different bulge fractions (see Fig. 3). In turn, this indicates that although early-type galaxies contain a higher fraction of the low-z metals in their bulges, the offset in metallicity between the highest and lowest metallicities at a given mass should also be the same. This explains the trends in Figures 1 and 2, that the galaxies with the highest metallicities at a given mass bin. There is no segregation in the MZR for galaxies with different metallicities (see Fig. 3). In turn, this indicates that although there is no significant difference in the MZR for galaxies with different metallicities (Kauffmann et al. 2003b), we find that there is no significant offset toward lower metallicities (by up to 0.2 dex) for galaxies with larger half-light radii and higher specific star formation rates, but that there is no significant dependence on bulge fraction. These dependencies have little impact on the overall scatter in the MZR and the basic shape of the relation exists for all subsets of and SSFR. We conclude that environment and abundance gradients are unlikely to account for (all of the) the and SSFR dependence of the MZR. Infall of metal-poor gas or metal-enriched outflows also seem unlikely explanations based on timescale arguments. Of the possibilities considered here, a sensitivity to star formation efficiency is the most plausible reason for the dependence of the MZR on and SSFR.

We are grateful to the Munich group for making their SDSS galaxy catalogs publicly available and to Lisa Kewley for providing her metallicity calibrations. We have benefited from insightful discussions with Alyson Brooks, Romaine Davé, Kristian Finlator, and Fabio Governato and from extremely useful feedback from the referee. S. L. E. and D. R. P. are supported by NSERC Discovery Grants.

5. CONCLUSIONS

We have investigated how the galactic MZR depends on observable parameters such as the half-light radius, SSFR, and morphology and discuss various scenarios to explain the dependencies. We find that at a given stellar mass, the MZR is offset toward lower metallicities (by up to 0.2 dex) for galaxies with larger half-light radii and higher specific star formation rates, but that there is no significant dependence on bulge fraction. These dependencies have little impact on the overall scatter in the MZR and the basic shape of the relation exists for all subsets of and SSFR. We conclude that environment and abundance gradients are unlikely to account for (all of the) the and SSFR dependence of the MZR. Infall of metal-poor gas or metal-enriched outflows also seem unlikely explanations based on timescale arguments. Of the possibilities considered here, a sensitivity to star formation efficiency is the most plausible reason for the dependence of the MZR on and SSFR.

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