

Clues to the Origin of the Mass-Metallicity Relation: Dependence on Star Formation Rate and Galaxy Size.

Sara L. Ellison¹, David R. Patton^{2,3}, Luc Simard⁴, & Alan W. McConnachie¹

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 magnitudes in M_B (e.g., Skillman, Kennicutt & Hodge 1989; Zaritsky, Kennicutt & Huchra 1994; Salzer et al. 2005; Lee et al. 2006) 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, Baldry & Bamford 2007) and remains intact out to $z \sim 2.5$ (Savaglio et al. 2005; Erb et al. 2006).

¹Dept. of Physics & Astronomy, University of Victoria, 3800 Finnerty Rd, Victoria, V8P 1A1, British Columbia, Canada, sarae@uvic.ca, alan@uvic.ca

²Department of Physics & Astronomy, Trent University, 1600 West Bank Drive, Peterborough, Ontario, K9J 7B8, Canada, dpatton@trentu.ca

³Visiting Researcher, Dept. of Physics & Astronomy, University of Victoria, 3800 Finnerty Rd, Victoria, V8P 1A1, British Columbia, Canada

⁴National Research Council of Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, British Columbia, V9E 2E7, Canada, luc.simard@nrc.ca

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., Kobayshi, Springel & White 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; Finalator & Davé 2007). In this paper, 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 $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, $H_0 = 70$ km/s/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 $14.5 < r \leq 17.77$ 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)¹. The galaxies must also have available metallicities from the Kewley & Dopita (2002) ‘recommended’ method, masses determined from spectral synthesis modelling (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 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 Sersic 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 2005; Kewley & Ellison 2007). The final sample consists of 43,690 galaxies with a median redshift of $z = 0.086$.

¹Using the AGN classification scheme of Kauffmann et al. (2003a) yields identical science results, but results in a sample of only 38703 galaxies, a reduction of $\sim 10\%$. This is in agreement with Kewley & Ellison (2007) who find that the AGN removal method does not affect the shape of the MZR.

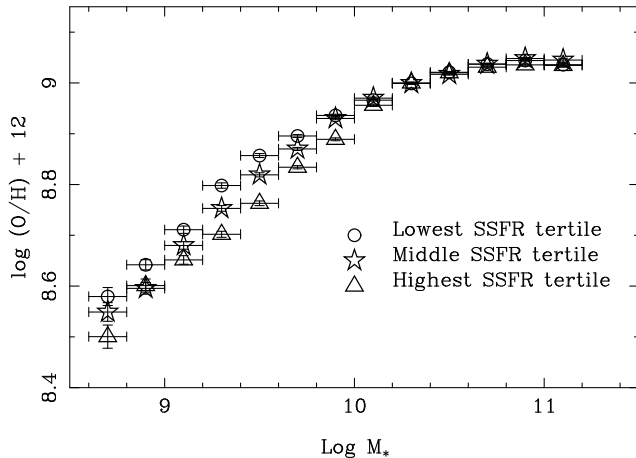


Fig. 1.— The binned mass-metallicity relation for $\sim 44,000$ SDSS galaxies from the DR4, divided by specific star formation rate, $\log \text{SSFR} = \log [\text{SFR} (M_{\odot}\text{yr}^{-1})/M_{\star}(M_{\odot})]$, tertiles in each mass bin. Open circles, stars and triangles represent the lowest, intermediate and highest SSFRs in units of $\log (\text{yr}^{-1})$ respectively. The divisions between the SSFR tertiles are $\log \text{SSFR} < -9.8 \text{ yr}^{-1}$, $-9.8 < \text{SSFR} < -9.6 \text{ yr}^{-1}$ and $\text{SSFR} > -9.6 \text{ yr}^{-1}$ for the mass bin centered at $\log M_{\star} = 9.5 M_{\odot}$ and $\text{SSFR} < -10.0 \text{ yr}^{-1}$, $-10.0 < \text{SSFR} < -9.7 \text{ yr}^{-1}$ and $\text{SSFR} > -9.7 \text{ yr}^{-1}$ for the mass bin centered at $\log M_{\star} = 10.5 M_{\odot}$. The vertical error bars are the standard error on the mean.

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 $\text{H}\alpha + [\text{NII}]$ equivalent width (EW), which is a measure of the present to past-average star formation rate (see Figure 3 of Kennicutt et al. 1994), of galaxies with $\log \text{SSFR} > -9.5$ is 56 \AA . 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 ($\log M_{\star} > 10 M_{\odot}$) 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 bins is $\sim 0.10 - 0.15$ dex in the stellar mass range $9 < \log M_{\star} < 10 M_{\odot}$ and is significant at greater than 5σ (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 towards 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

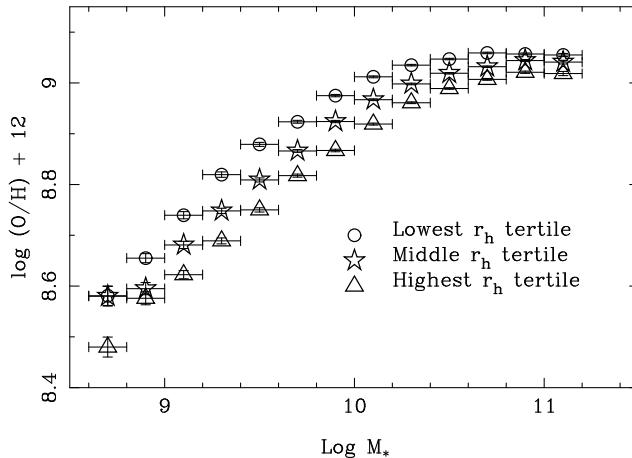


Fig. 2.— The binned mass-metallicity relation for $\sim 44,000$ SDSS galaxies from the DR4, divided by half light radius (r_h) tertiles in each mass bin. Open circles, stars and triangles represent the lowest, intermediate and highest r_h respectively. The divisions between the r_h tertiles are $r_h < 2.2 h_{70}^{-1}$ kpc, $2.2 < r_h < 3.3 h_{70}^{-1}$ kpc and $r_h > 3.3 h_{70}^{-1}$ kpc for the mass bin centered at $\log M_\star = 9.5 M_\odot$ and $r_h < 4.0 h_{70}^{-1}$ kpc, $4.0 < r_h < 5.5 h_{70}^{-1}$ kpc and $r_h > 5.5 h_{70}^{-1}$ kpc for the mass bin centered at $\log M_\star = 10.5 M_\odot$. The vertical error bars are the standard error on the mean.

the largest half light radii, with a range in the binned values of between 0.05 – 0.2 dex. A similar result was noted by Tremonti et al. (2004), who found that, for a fixed M_\star , 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 $9 < \log M_\star < 10 M_\odot$ is greater than 10σ 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

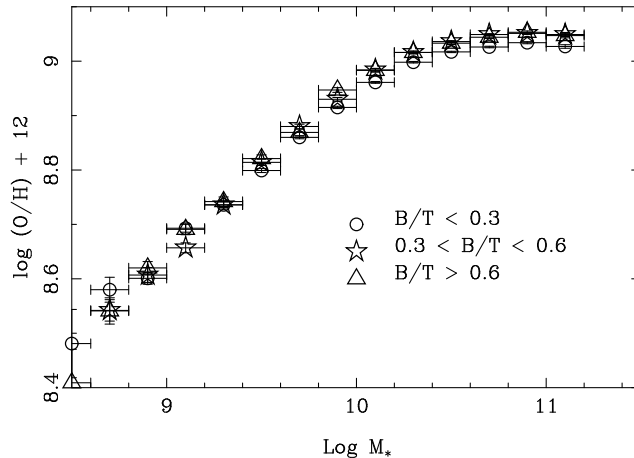


Fig. 3.— The binned mass-metallicity relation for $\sim 44,000$ SDSS galaxies from the DR4, divided by r -band bulge-to-total fraction (B/T). Open circles, stars and triangles represent $B/T < 0.3$, $0.3 \leq B/T < 0.6$ and $B/T \geq 0.6$ respectively. The vertical error bars are the standard error on the mean.

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 ultra-luminous infra-red 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 2005; 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 high redshift LBG is $\sim 2 h_{70}^{-1}$ kpc (Dickinson 2000), which could potentially result in an upward shift in their observed MZR (see Figure 2). Conversely, LBGs tend to have quite high SSFRs; all of the binned SSFRs in Erb et al. (2006) have values of $\log \text{SSFR} \geq -9.3 \text{ yr}^{-1}$, which would result in a downwards shift in their MZR (see Figure 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 $r_h \leq 2 h_{70}^{-1}$ kpc and $\text{SSFR} \geq 9.3 \text{ yr}^{-1}$ (the ‘LBG-like’ sample). We find

that the LBG-like sample has a small negative offset, i.e., to lower metallicities, by ~ 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 Figure 1), the effect of the r_h dependence is dominant and the MZR of the LBG-like galaxies is positively offset by ~ 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_h . The median CFs are 0.40, 0.29 and 0.24 for the smallest, intermediate and largest r_h 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_h galaxies (whose CF is large), opposite to what we find in Figure 2. However, if the steepness of abundance gradients depends on r_h 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_h . On the one hand, nearby dwarfs tend to have very flat abundance gradients (e.g., Lee, Skillman & Venn 2006). 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_h 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_h and covering fraction, where the presence of r_h -dependent gradients plus aperture effects would manifest themselves as a smaller segregation by r_h 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_h dependence seen in Figure 2.

Galactic winds. Winds may seem like a natural explanation for the dependence of the MZR on r_h 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 HII phase. Moreover, whilst galaxies with smaller r_h 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 infall/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 (Finlator, 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, $t_d = M_{\text{gas}}/\dot{M}_{\text{acc}}$, where M_{gas} is the gas mass and \dot{M}_{acc} is the gas accretion rate. If $t_d < t_{\text{dyn}}$ (where t_{dyn} is the dynamical time) then the galaxy ‘recovers’ its equilibrium metallicity promptly, leading to very little scatter in the MZ relation. Conversely, if $t_d > t_{\text{dyn}}$, 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 $t_{\text{dyn}} \propto \sqrt{r^3/M_{\text{gal}}}$, then, all other things being equal, $t_d/t_{\text{dyn}} \propto r^{-3/2}$.

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 towards lower metallicities for smaller r_h 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_h dependence is seen in the galaxy sample considered here, with small r_h 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. Whilst galaxy interactions can perturb the LZR and MZR (Kewley et al. 2006; Rupke et al. 2007), the dependence of this effect on r_h is the opposite to that seen in Figure 2 (Ellison et al. 2007). Moreover, Ellison et al. (2007) attributed the r_h dependence of the MZR in galaxy pairs to the stabilizing effect of a bulge (e.g., Mihos & Hernquist 1994, 1996; Cox et al. 2007). We find that there is no significant difference in the MZR for galaxies with different bulge fractions, see Figure 3. In turn, this indicates that although early-type galaxies contain a higher fraction of the low z metals budget (e.g., Gallazzi et al. 2007), morphology does not appear to segregate the MZR.

Star formation efficiencies. Differing star formation efficiencies (SFE) is another possible explanation for the trends in Figures 1 and 2. If the gas (as well as light) is more centrally located in small r_h galaxies, and has a higher surface density, this could lead to higher SFE in the past. In turn, this would yield higher present-day gas-phase metallicities but lower current SSFRs if more of the gas has been depleted as a result of the past star formation. A prediction of this scenario, which explains the trends in Figures 1 and 2, is that the galaxies with the highest metallicities at a given mass should also be the reddest and have the lowest $\text{H}\alpha + [\text{NII}]$ EW (a measure of present to past-average star formation, Kennicutt et al. 1994). These effects are indeed present in the data. Based on the GIM2D bulge and disk magnitudes, we find that galaxies in the reddest $(g - r)_{\text{disk}}$ tertile at $\log M_\star = 9.5 M_\odot$ have a median metallicity 0.2 dex greater than the bluest tertile of galaxies in the same mass bin. There is no segregation in the MZR for bulge colors. The offset in metallicity between the highest and lowest $\text{H}\alpha + [\text{NII}]$ EW tertiles at the same stellar mass is 0.1 dex. Kauffmann et al. (2003b) have similarly concluded that star formation histories are most sensitive to surface mass density.

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 towards 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 r_h and SSFR. We conclude that environment and abundance gradients are unlikely to account for (all) of the r_h 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 r_h 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 benefitted from insightful discussions with Alyson Brooks, Romeel Davé, Kristian Finlator and Fabio Governato and from extremely useful feedback from the referee. SLE and DRP are supported by NSERC Discovery Grants.

REFERENCES

- Blanton, M. R., et al. 2005, *AJ*, 129, 2562
- Brinchmann, J., Charlot, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., Brinkmann, J., 2004, *MNRAS*, 351, 1151
- Brooks, A. M., Governato, F., Booth, C. M., Willman, B., Gardner, J. P., Wadsley, J., Stinson, G., Quinn, T., 2007, *ApJ*, 655, L17
- Cox, T. J., Jonsson, P., Somerville, R. S., Primack, J. R., Dekel, A., *MNRAS*, 2007, submitted
- Dalcanton, J. J., 2007, *ApJ*, 658, 941
- Dickinson, M., 2000, *Philos. Trans. R. Soc. London A*, 358, 2001
- Ellison, S. L., Patton, D. R., Simard, L., McConnachie, A. W., 2007, *AJ*, submitted

- Ellison, S. L., Kewley, L. J., 2005, pg 53, Proceedings of "The Fabulous Destiny of Galaxies; Bridging the Past and Present", Eds Le Brun, Mazure, Arnouts, Burgarella
- Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A., Adelberger, K. L., 2006, *ApJ*, 644, 813
- Finlator, K., & Davé, R., 2007, *MNRAS*, submitted, arXiv:0704.3100
- Gallazzi, A., Brinchmann, J., Charlot, S., White, S. D. M., 2007, *MNRAS*, submitted, arXiv:0708.0533
- Gallazzi, A., Charlot, S., Brinchmann, J., White, S. D. M., Tremonti, C. A., 2005, *MNRAS*, 362, 41
- Hoopes, C. G., et al., 2007, *ApJS*, in press, arXiv:astro-ph/0609415v1
- Kauffmann, G., et al., 2003a, *MNRAS*, 346, 1055
- Kauffmann, G., et al., 2003b, *MNRAS*, 341, 33
- Kennicutt, R. C., Tamblyn, P., Congdon, C. E., 1994 *ApJ*, 435, 22
- Kewley, L. J., & Dopita, M. A., 2002, *ApJS*, 142, 35
- Kewley, L. J., & Ellison, S. L., 2007, *ApJ*, submitted
- Kewley, L. J., Heisler, C. A., Dopita, M. A., Lumsden, S., 2001, *ApJS*, 132, 37
- Kewley, L. J., Jansen, R. A., Geller, M. J., 2005, *PASP*, 117, 227
- Kobayashi, C., Springel, V., & White, S. D. M., 2007, *MNRAS*, 376, 1465
- Lee, H., Skillman, E. D., Cannon, J. M., Jackson, D. C., Gehrz, R. D., Polomski, E. F., Woodward, C. E., 2006, *ApJ*, 647, 970
- Lee, H., Skillman, E. D., Venn, K. A., 2006, *ApJ*, 642, 813
- Lequeux, J., Peimbert, M., Rayo J. F., Serrano, A., Torres-Peimbert, S., 1979, *A&A*, 80, 155
- Magrini, L., Vilchez, J. M., Mampaso, A., Corradi, R. L. M., Leisy, P., 2007, *A&A*, 470, 865
- Martin, P., & Roy, J.-R., 1995, *ApJ*, 445, 161
- Mihos, C., & Hernquist, L., 1994, *ApJ*, 425, L13
- Mihos, C., & Hernquist, L., 1996, *ApJ*, 464, 641

- Mouhcine, M., Baldry, I. K., Bamford, S. P., 2007, MNRAS accepted, arXiv:0709.3794
- Prantzos, N., Boissier, S., 2000, MNRAS, 313, 338
- Rupke D. S. N., Veilleux, S., & Baker, A. J., 2007, ApJ, accepted, arXiv:0708.1766
- Salzer, J. J., Lee, J. C., Melbourne, J., Hinz, J. L., Alonso-Herrero, A., Jangren, A., 2005, ApJ, 624, 661
- Savaglio, S., et al., 2005, ApJ, 635, 260
- Simard, L., Willmer, C. N. A., Vogt, N. P., Sarajedini, V. L., Phillips, A. C., Weiner, B. J., Koo, D. C., Im, M., Illingworth, G. D., Faber, S. M., 2002, ApJS, 142, 1
- Skillman, E. D., Kennicutt, R. C., & Hodge, P. W., ApJ, 1989, 347, 875
- Zaritsky, D., Kennicutt, R. C., Jr., Huchra, J. P., 1994, ApJ, 420, 87