*R*esearch in
*A*stronomy and
*A*strophysics

The Evolution of Advanced Merger (U)LIRGs on the Color-Stellar Mass Diagram

Rui Guo[1,2,3], Cai-Na Hao[3] and Xiao-Yang Xia[3]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Tianjin Astrophysics Center, Tianjin Normal University, Tianjin 300387, China; *cainahao@gmail.com*

Abstract Based on a sample of 79 local advanced merger (adv-merger) (U)LIRGs, we search for evidence of quenching processes by investigating the distributions of star formation history indicators (EW(Hα), EW(Hδ_A) and D$_n$(4000)) on the *NUV-r* color-mass and SFR-M_* diagrams. The distributions of EW(Hα) and D$_n$(4000) on the *NUV-r* color-mass diagram show clear trends that at a given stellar mass, galaxies with redder *NUV-r* colors have smaller EW(Hα) and larger D$_n$(4000). The reddest adv-merger (U)LIRGs close to the green valley mostly have D$_n$(4000)> 1.4. In addition, in the SFR-M_* diagram, as the SFR decreases, the EW(Hα) decreases and the D$_n$(4000) increases, implying that the adv-merger (U)LIRGs on the star formation main sequence have more evolved stellar populations than those above the main sequence. These results indicate that a fraction of the adv-merger (U)LIRGs have already exhibited signs of fading from the starburst phase and that the *NUV-r* reddest adv-merger (U)LIRGs are likely at the initial stage of post-starbursts with an age of ~ 1 Gyr, which is consistent with the gas exhaustion time-scales. Therefore, our results offer additional support for the fast evolutionary track from the blue cloud to the red sequence.

Key words: galaxies: evolution — galaxies: formation — galaxies: interactions — galaxies: starburst — infrared: galaxies

1 INTRODUCTION

Since the discovery of color bimodality on the color-magnitude and color-stellar mass (color-mass hereafter) diagrams based on the Sloan Digital Sky Survey (SDSS) (Kauffmann et al. 2003a; Baldry et al. 2004, 2006) as well as on high redshift survey samples (Bell et al. 2004; Faber et al. 2007; Ilbert et al. 2010), there have been mounting works that investigate the evolutionary pathways from the blue cloud of star-forming galaxies to the red sequence of quiescent galaxies. The evolution from the blue cloud to the red sequence is suggested to result from star formation being quenched (e.g., Faber et al. 2007). According to the quenching time-scales, the evolutionary tracks are classified into fast and slow modes (e.g., Schawinski et al. 2014; Yesuf et al. 2014). The fast track (with time-scales less than 1 Gyr) has been proposed to interpret the formation of high redshift compact massive quiescent galaxies (van Dokkum et al. 2008; Kriek et al. 2009; Barro et al. 2013; Muzzin et al. 2013; Marchesini et al. 2014). These studies show that the progenitors of local massive galaxies are heavily dust-extincted starburst galaxies that are triggered by gas-rich major mergers. Therefore, investigation of local gas-rich major mergers might shed light on the fast quenching process.

In the local universe, almost all ultraluminous infrared galaxies (ULIRGs; $L_{\mathrm{IR}}[1]> 10^{12}L_\odot$) and about half of luminous infrared galaxies (LIRGs; $10^{11}L_\odot < L_{\mathrm{IR}} < 10^{12}L_\odot$) were found to be gas-rich interacting/merging galaxies (e.g. Sanders & Mirabel 1996; Wang et al. 2006; Kaviraj 2009). Therefore, nearby (U)LIRGs can serve as a proper local laboratory for studying the fast quenching process. Several recent works have made efforts to identify the role of local ULIRGs in the migration from the blue cloud to the red sequence. Chen et al. (2010) and Kilerci Eser et al. (2014) have investigated the positions of local ULIRGs in the *g-r* and *u-r* color-magnitude diagrams, respectively, without applying internal extinction corrections. They found that about half of the ULIRG sample lies outside the 90% level number density contour, and some are in the green valley or the red sequence. More recently, Guo et al. (2016a) applied both Galactic and internal dust extinction corrections for a sample of advanced merger (adv-merger) (U)LIRGs and found that adv-merger (U)LIRGs are bluer and more massive than the blue cloud galaxies, with $95\% \pm 2\%$ and $81\% \pm 4\%$ of them outside the blue cloud on the *u-r* and *NUV-r* color-mass diagrams, respectively, implying that the adv-merger (U)LIRGs oc-

---

[1] L_{IR} is the integrated infrared luminosity between 8–1000 μm.

cupy a distinct region on the color-mass diagrams. In addition, the investigation of the locus of the adv-merger (U)LIRGs in the star formation rate (SFR)-stellar mass (SFR-M_*) diagram showed that about two-thirds of the sample are above the star-forming main sequence, indicating that the majority of adv-merger (U)LIRGs are experiencing massive starbursts. Based on the estimates of gas exhaustion time-scales, the authors suggested that adv-merger (U)LIRGs are likely at the starting point of the fast evolutionary track.

As is well known, the equivalent width of $H\delta_A$ absorption line (EW($H\delta_A$)) and the 4000 Å break ($D_n(4000)$) measured from optical spectra are powerful indicators of recent star formation histories. A strong $H\delta_A$ absorption line is a sign for a burst in the star formation history that ended about 0.1–1 Gyr ago, while the 4000 Å break is an excellent age indicator for young star populations within 1 Gyr (Kauffmann et al. 2003a,b). As a result, EW($H\delta_A$) and $D_n(4000)$ are often used to probe recent starbursts and distinguish star formation histories dominated by starbursts from a continuous mode (Kauffmann et al. 2003a; Goto 2007; Martin et al. 2007; Yesuf et al. 2014). In addition, the equivalent width of $H\alpha$, EW($H\alpha$), is a measure of the current to past average SFR (e.g., Knapen & James 2009; Yesuf et al. 2014).

To explore the evolutionary link between starburst galaxies and post-starbursts, Yesuf et al. (2014) proposed a classification scheme to identify transiting post-starbursts, an intermediate stage between starbursts and post-starbursts, based on EW($H\alpha$), EW($H\delta_A$), $D_n(4000)$, UV and *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010) photometry. Guo et al. (2016a) employed this set of criteria and identified 12 transiting post-starbursts out of the entire sample of 89 adv-merger (U)LIRGs. It is also worth carefully investigating the distributions of the spectral features of EW($H\alpha$), EW($H\delta_A$) and $D_n(4000)$ on the color-mass and SFR-mass diagrams to search for evidence of possible evolutionary signs already shown in the adv-merger (U)LIRGs sample.

This paper is structured as follows. In Section 2 we describe the sample selection and parameter estimations for our sample of adv-mergers and control samples. In Section 3, we present our results and discussion. The main results are summarized in Section 4. Throughout this paper we adopt the Kroupa (2001) initial mass function and a cosmological model of $H_0 = 70 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.3$ and $\Omega_\Lambda = 0.7$.

2 SAMPLE SELECTION AND PARAMETER ESTIMATIONS

2.1 Sample

Our adv-merger (U)LIRG sample is directly taken from Guo et al. (2016a). We refer the readers to that paper for a detailed description of the sample selection (see also Guo et al. 2016b). In the following, we briefly describe the selection procedures.

The parent (U)LIRG sample in Guo et al. (2016a) was drawn from a cross-correlation analysis between the spectroscopic catalog of SDSS DR7 (York et al. 2000; Abazajian et al. 2009) and the *Infrared Astronomical Satellite (IRAS)* Point Source Catalog Redshift Survey (PSCz, Saunders et al. 2000), as well as a cross-identification between the *IRAS* 1 Jy ULIRG sample (Kim & Sanders 1998) and the SDSS DR7 photometric catalog. We performed morphological classifications visually for the sub-sample of galaxies in the magnitude range of $14.5 < r < 15.9^2$ after corrections for foreground Galactic extinction (Schlegel et al. 1998), to ensure both reliable morphological classifications and spectroscopic completeness for SDSS galaxies (Fukugita et al. 2004; Kauffmann et al. 2003a). Note that galaxies classified as Seyfert I are removed from our sample, since the estimations for their extinctions, stellar masses and star formation rates are not reliable. Finally, there are 89 adv-mergers selected, which are in the late merging stage. For the purpose of this work, measurements of optical spectral indices are needed. Hence only the 79 adv-mergers with SDSS spectroscopic observations are included in this paper, among which 59 are LIRGs and 20 are ULIRGs. Figure 1 shows the true color images of 16 example adv-mergers.

Meanwhile, the control samples are also taken from Guo et al. (2016a) directly. For the study of the local color-mass relation, the control sample was selected from the Oh-Sarzi-Schawinski-Yi (OSSY) catalog (Oh et al. 2011)³, which provides internal extinction information (E($B-V$)) from stellar continuum fits. By requiring the redshift range of $0.02 < z < 0.05$ and absolute magnitude $M_{z,\mathrm{Petro}} < -19.5$ mag, 53 604 galaxies were obtained. The absolute magnitude constraint enables us to derive an approximately mass-limited sample as described in Schawinski et al. (2014). For investigating the SFR-M_* relation of star-forming galaxies, the control sample has been retrieved from the SDSS DR7 in the redshift range of $0.005 < z < 0.2$ and luminosity range of $14.5 < r < 17.77$, which consists of 152 137 galaxies.

2.2 Parameters

The main purpose of this paper is to investigate the distributions of EW($H\alpha$), EW($H\delta_A$) and $D_n(4000)$ on the *NUV-r* color-stellar mass as well as the SFR-stellar mass diagrams. Therefore, apart from the estimates of dust extinction corrected *NUV-r* colors, SFRs and stellar masses, as described in Guo et al. (2016a), optical spectral indices are also needed.

The estimations of the dust attenuation corrected *NUV-r* colors, SFRs and stellar masses have been described in Guo et al. (2016a). We only provide a brief description here. The optical photometric data and *NUV* magnitudes were taken from the SDSS DR7 and the *Galaxy Evolution*

---

² The magnitude restriction was not performed for the 1 Jy ULIRGs since they have obvious interacting or merging morphologies.

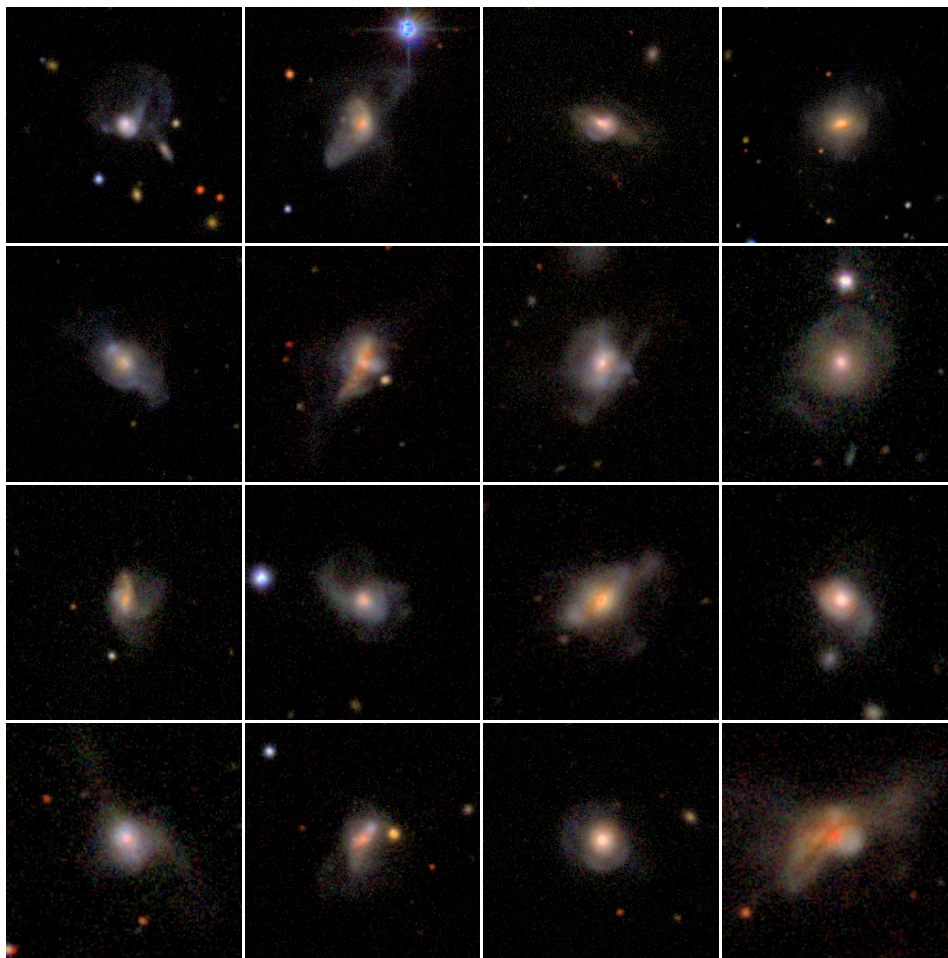³ *http://gem.yonsei.ac.kr/~ksoh/wordpress*

Fig. 1 RGB color images of 16 example adv-mergers with a single nucleus but some merger signatures, e.g., tidal tails, indicating that they are in the late stage of merging. The images are constructed from SDSS (*g, r, i*) images following Lupton et al. (2004) with a physical size of $80 \times 80 \, \mathrm{kpc}^2$.

Explorer (GALEX) satellite (Martin et al. 2005), respectively. The *NUV* photometric data are available from the *GALEX* archive for 69 sample adv-merger (U)LIRGs and $\sim 87\%$ control sample galaxies. We further performed *k*-corrections, as well as corrections for Galactic extinction and internal extinction to the optical and *NUV* magnitudes. The stellar masses for our sample adv-mergers and the control sample galaxies were retrieved from the Max Planck Institute for Astrophysics-Johns Hopkins University (MPA/JHU[4]) stellar mass catalog (Kauffmann et al. 2003a), which are based on the five broad-band photometry provided by SDSS. The SFRs for 25 star-forming and 38 composite[5] adv-merger (U)LIRGs were calculated using their Hα luminosities taken from the MPA/JHU catalog following Kennicutt (1998) and then were converted to a Kroupa initial mass function. Note that the Hα luminosities are aperture-corrected (Hopkins et al. 2003) as well as dust extinction corrected under the assumption of the case B recombination value for intrinsic Hα/Hβ being 2.86.

---

[4] *http://www.mpa-garching.mpg.de/SDSS*
[5] The spectral classifications were performed according to the BPT diagram (Baldwin et al. 1981; Kauffmann et al. 2003c; Kewley et al. 2001).

The $\mathrm{D}_n(4000)$, EW(Hα) and EW(Hδ_A) were retrieved from the MPA/JHU catalog, in which the EW(Hδ_A) has been corrected for contamination by nebular emission. We further performed the internal extinction corrections for $\mathrm{D}_n(4000)$ and EW(Hα), using Calzetti's law (Calzetti et al. 2000).

3 RESULTS AND DISCUSSION

As presented in Guo et al. (2016a), most of the adv-merger (U)LIRGs in our sample are located above the star-forming main sequence on the SFR-M_* diagram, indicating that they are experiencing massive starbursts which are triggered by gas-rich major mergers. All these galaxies are blue and massive, and thus lie to the right of the blue cloud galaxies on the optical and *NUV* color-mass diagrams, making them distinct from the blue cloud, red sequence and green valley galaxies. These properties suggest that they are at the starting point of the fast track of galaxy evolution from the blue cloud to the red sequence. Therefore, it is interesting to ask whether they have already shown an evolutionary trend, as imprinted in their star formation history indicators. In this work, we investi–

gate the distributions of the star formation history indicators EW(Hα), EW(Hδ_A) and D$_n$(4000) on the color-mass and SFR-mass diagrams to search for evidence of possible evolution among the adv-merger (U)LIRG sample.

3.1 Distributions of EW(Hα), EW(Hδ_A) and D$_n$(4000) in the *NUV-r* Color-Mass Diagram

Although a large fraction of adv-merger (U)LIRGs in our sample are undergoing massive starbursts, the optical spectra of several galaxies in our sample already present clear K+A like features.

Figure 2 shows the example spectra of two such galaxies, from which we can clearly see the K+A like spectroscopic signatures, i.e., weak Hα emission, strong Hδ_A absorption line and deep 4000 Å break. These features indicate that a small fraction of adv-merger (U)LIRGs are more evolved than the others under the assumption that the adv-merger (U)LIRGs have similar star formation histories.

To obtain a visual view of the evolution, we use different colors to represent the EW(Hα), EW(Hδ_A) and D$_n$(4000) values on the *NUV-r* color-mass diagram, shown in the left, middle and right panels of Figure 3, respectively. It is clear from the middle panel of Figure 3 that the EW(Hδ_A) values for most sample galaxies are larger than 4 Å, indicating A-type star features from a burst in the recent past. In the left and right panels of Figure 3, there are obvious trends that the redder the galaxies are on the *NUV-r* color-mass diagram, the smaller the EW(Hα) and the larger the D$_n$(4000) are. The reddest adv-merger (U)LIRGs close to the green valley mostly have D$_n$(4000)> 1.4. We note that such trends are not caused by the correlation between the stellar mass and the EW(Hα) or D$_n$(4000), as manifested by the apparent trends shown at a given stellar mass. Taking into account the evolutionary picture as traced by the D$_n$(4000) and EW(Hδ_A) for an instantaneous starburst by Kauffmann et al. (2003a), the adv-merger (U)LIRGs with redder *NUV-r* colors are likely close to the end of starbursts or at the initial stage of post-starbursts according to the definitions by Goto (2007), Martin et al. (2007) and Yesuf et al. (2014). Therefore, from the distributions of the EW(Hα), EW(Hδ_A) and D$_n$(4000) values on the *NUV-r* diagram in Figure 3, we can clearly see the evolutionary trend from starbursts with blue *NUV-r* colors ($\sim$ 0.5 mag) to relatively older populations with redder colors ($\sim$ 3 mag) that formed in recent starbursts within the past $\sim$ 1 Gyr. This is consistent with the gas exhaustion time-scales as estimated in Guo et al. (2016a). This adds additional evidence for the fast evolutionary pathway to the conclusion drawn by Guo et al. (2016a).

3.2 Distributions of EW(Hα), EW(Hδ_A) and D$_n$(4000) in the SFR-M_* Diagram

It has been accepted that the SFR-M_* relation reflects the star formation modes: galaxies on the star formation main sequence form stars in a relatively steady mode, while galaxies localized above the main sequence line form stars in a starburst mode (Rodighiero et al. 2011; Hung et al. 2013). From the analysis for adv-merger (U)LIRGs, Guo et al. (2016a) found that about two-thirds of adv-merger (U)LIRGs are located above the 1σ line of the local star-forming galaxy main sequence and one-third of the sample galaxies lie on the main sequence. Therefore, it is essential to investigate the reasons responsible for the difference between the galaxies above the main sequence and those on the main sequence. On the other hand, it is a complement to Section 3.1 to witness the evolution of stellar populations on the SFR-M_* diagram.

Similar to Figure 3, different colors are used to denote the EW(Hα), EW(Hδ_A) and D$_n$(4000) values for each sample galaxy on the SFR-M_* diagram, shown in the left, middle and right panels of Figure 4, respectively. It is clear from the left and right panels of Figure 4 that at a given stellar mass, there are clear trends that as the SFR decreases, the EW(Hα) decreases and the D$_n$(4000) increases. In addition, the sample galaxies on the main sequence have relatively smaller EW(Hδ_A) on average. These results suggest that the adv-merger (U)LIRGs localized on the main sequence are more evolved counterparts of those above the main sequence, and they have started to fade from the starburst stage, as indicated by their smaller EW(Hα) and larger D$_n$(4000). According to the starburst age estimated by D$_n$(4000) (Kauffmann et al. 2003a), these adv-merger (U)LIRGs are going to leave the main sequence towards low SFRs in the SFR-M_* diagram in $\sim$ 1 Gyr. The evolution of the spectral indices on the SFR-M_* diagram depicts a coherent picture with that exhibited by Figure 3.

4 SUMMARY

With the aim of studying the fast quenching process from the blue cloud to the red sequence, we retrieve 79 local adv-merger (U)LIRGs with SDSS spectroscopic observations from Guo et al. (2016a) and investigate the distributions of EW(Hα), EW(Hδ_A) and D$_n$(4000) on the *NUV-r* color-mass and SFR-M_* diagrams. The distributions of EW(Hα), EW(Hδ_A) and D$_n$(4000) values on the *NUV-r* color-mass and SFR-M_* diagrams of adv-merger (U)LIRGs show obvious evolutionary trends: at a given stellar mass, galaxies with redder *NUV-r* colors or lower SFRs have smaller EW(Hα) and larger D$_n$(4000), indicating more evolved stellar populations. Moreover, most of the reddest adv-merger (U)LIRGs close to the green valley have D$_n$(4000)> 1.4 and the majority of our sample galaxies have EW(Hδ_A) > 4 Å that is a sign for A-type star features from a recent starburst in the past $0.1 - 1$ Gyr. These results suggest that some of the adv-merger (U)LIRGs have already shown signs of fading from the starburst stage and the reddest adv-merger (U)LIRGs in *NUV-r* color are likely at the initial stage of post-starbursts with an age of $\sim$ 1 Gyr. This time-scale coincides with the gas depletion time-scales derived by Guo et al. (2016a). Therefore,
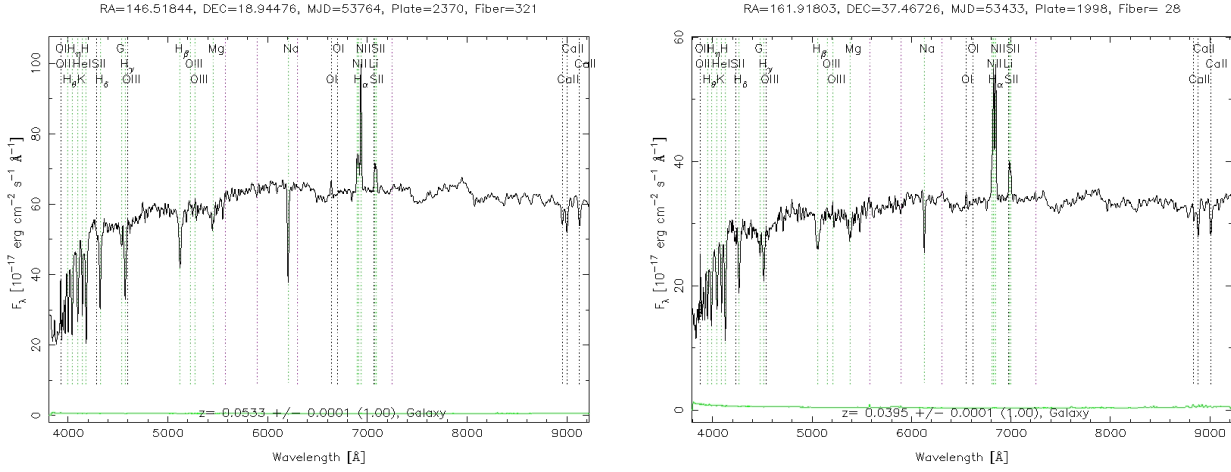
Fig. 2 SDSS spectra for two example adv-merger (U)LIRGs with weak Hα emissions, strong Hδ$_A$ absorptions and deep 4000 Å breaks.
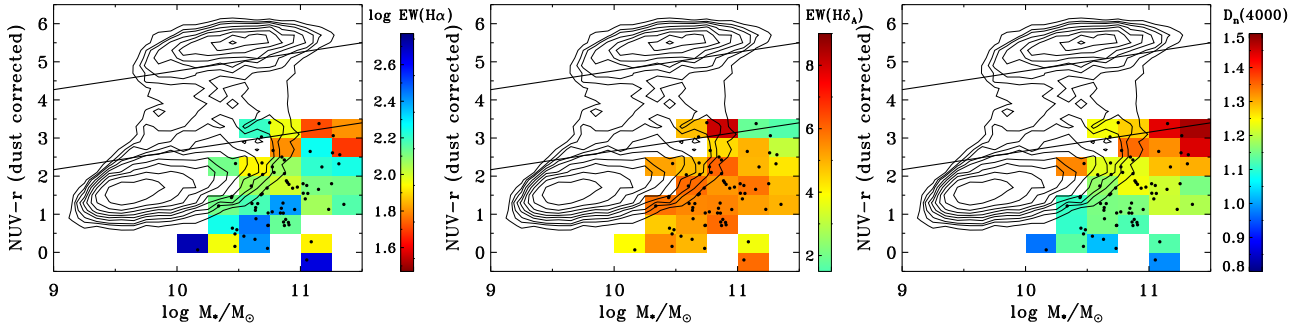

Fig. 3 Dust-corrected *NUV-r* color-mass diagrams for 69 sample adv-merger (U)LIRGs with both *NUV* photometry from the *GALEX* archive and spectra from SDSS. The contours represent nine equally spaced levels between 10% and 90% number densities of 46 407 control sample galaxies with *NUV* photometry. Black solid lines show the boundaries of the green valley (eqs. (7) and (8) from Guo et al. (2016a)). Dust extinction corrected EW(Hα) (*left*), EW(Hδ$_A$) (*middle*) and D$_n$(4000) (*right*) distributions are overlaid. The color scales are shown in the right part of each panel.
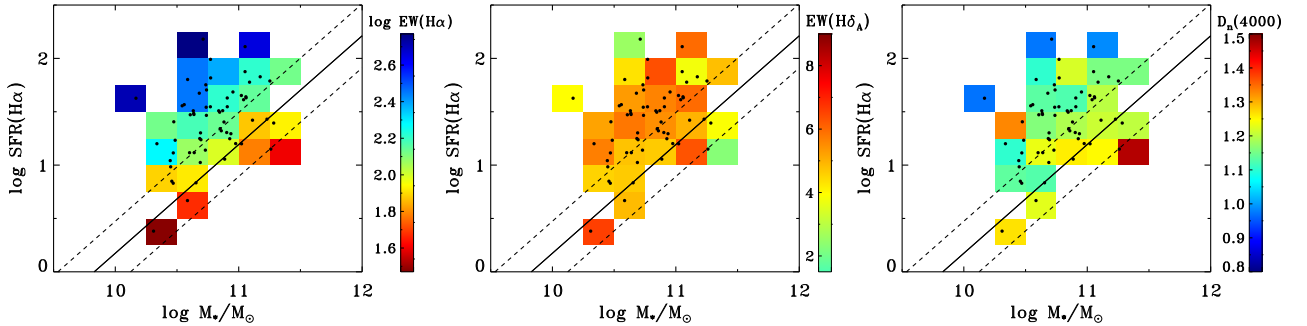
Fig. 4 SFR(Hα) vs. stellar mass relations for 63 adv-merger (U)LIRGs with either star-forming or composite spectral features. The black solid line indicates the local star-forming main sequence (eq. (4) from Guo et al. (2016a)) with 1σ dispersions (0.3 dex) shown as dashed lines. Dust extinction corrected EW(Hα) (*left*), EW(Hδ$_A$) (*middle*) and D$_n$(4000) (*right*) distributions are overlaid. The color scales are shown in the right part of each panel.

our results add additional support for the fast evolutionary track proposed by several groups (e.g. Muzzin et al. 2013; Barro et al. 2013, 2014a,b; Marchesini et al. 2014; Schawinski et al. 2014; Belli et al. 2015; Wellons et al. 2015).

References

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Baldry, I. K., Balogh, M. L., Bower, R. G., et al. 2006, MNRAS, 373, 469

Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5

Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2013, ApJ, 765, 104

Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2014a, ApJ, 791, 52

Barro, G., Trump, J. R., Koo, D. C., et al. 2014b, ApJ, 795, 145

Bell, E. F., Wolf, C., Meisenheimer, K., et al. 2004, ApJ, 608, 752

Belli, S., Newman, A. B., & Ellis, R. S. 2015, ApJ, 799, 206

Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682

Chen, Y., Lowenthal, J. D., & Yun, M. S. 2010, ApJ, 712, 1385

Faber, S. M., Willmer, C. N. A., Wolf, C., et al. 2007, ApJ, 665, 265

Fukugita, M., Nakamura, O., Turner, E. L., Helmboldt, J., & Nichol, R. C. 2004, ApJ, 601, L127

Goto, T. 2007, MNRAS, 381, 187

Guo, R., Hao, C.-N., Xia, X. Y., Mao, S., & Shi, Y. 2016a, arXiv:1604.07122 (ApJ, in press)

Guo, R., Hao, C.-N., Xia, X.-Y., Wei, P., & Guo, X. 2016b, RAA (Research in Astronomy and Astrophysics), 16, 113

Hopkins, A. M., Miller, C. J., Nichol, R. C., et al. 2003, ApJ, 599, 971

Hung, C.-L., Sanders, D. B., Casey, C. M., et al. 2013, ApJ, 778, 129

Ilbert, O., Salvato, M., Le Floc'h, E., et al. 2010, ApJ, 709, 644

Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003a, MNRAS, 341, 33

Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003b, MNRAS, 341, 54

Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003c, MNRAS, 346, 1055

Kaviraj, S. 2009, MNRAS, 394, 1167

Kennicutt, Jr., R. C. 1998, ARA&A, 36, 189

Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 556, 121

Kilerci Eser, E., Goto, T., & Doi, Y. 2014, ApJ, 797, 54

Kim, D.-C., & Sanders, D. B. 1998, ApJS, 119, 41

Knapen, J. H., & James, P. A. 2009, ApJ, 698, 1437

Kriek, M., van Dokkum, P. G., Franx, M., Illingworth, G. D., & Magee, D. K. 2009, ApJ, 705, L71

Kroupa, P. 2001, MNRAS, 322, 231

Lupton, R., Blanton, M. R., Fekete, G., et al. 2004, PASP, 116, 133

Marchesini, D., Muzzin, A., Stefanon, M., et al. 2014, ApJ, 794, 65

Martin, D. C., Fanson, J., Schiminovich, D., et al. 2005, ApJ, 619, L1

Martin, D. C., Wyder, T. K., Schiminovich, D., et al. 2007, ApJS, 173, 342

Muzzin, A., Marchesini, D., Stefanon, M., et al. 2013, ApJS, 206, 8

Oh, K., Sarzi, M., Schawinski, K., & Yi, S. K. 2011, ApJS, 195, 13

Rodighiero, G., Daddi, E., Baronchelli, I., et al. 2011, ApJ, 739, L40

Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749

Saunders, W., Sutherland, W. J., Maddox, S. J., et al. 2000, MNRAS, 317, 55

Schawinski, K., Urry, C. M., Simmons, B. D., et al. 2014, MNRAS, 440, 889

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

van Dokkum, P. G., Franx, M., Kriek, M., et al. 2008, ApJ, 677, L5

Wang, J. L., Xia, X. Y., Mao, S., et al. 2006, ApJ, 649, 722

Wellons, S., Torrey, P., Ma, C.-P., et al. 2015, MNRAS, 449, 361

Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868

Yesuf, H. M., Faber, S. M., Trump, J. R., et al. 2014, ApJ, 792, 84

York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579