THE STAR FORMATION MAIN SEQUENCE: THE DEPENDENCE OF SPECIFIC STAR FORMATION RATE AND ITS DISPERSION ON GALAXY STELLAR MASS

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ABSTRACT

The dispersion of the star formation main sequence (SFMS) reflects the diversity of star formation histories (SFHs) and variation in star formation rates (SFRs) in star-forming galaxies (SFGs) with similar stellar masses (M\(^{*}\)). We examine the dispersion of the local SFMS using a complete sample of Sloan Digital Sky Survey galaxies at 0.01 < z < 0.03 with log(M\(^{*}\)/M\(_{\odot}\)) > 8.8. The SFRs are estimated from H\(_{\alpha}\) in combination with 22 \(\mu\)m observation from the Wide-field Infrared Survey Explorer. We measure the dispersion of specific SFRs (sSFRs) as a function of M\(^{*}\). We confirm that the dispersion increases with M\(^{*}\) from 0.37 ± 0.01 dex at log(M\(^{*}\)/M\(_{\odot}\)) < 9.6 to 0.51 ± 0.02 dex at log(M\(^{*}\)/M\(_{\odot}\)) > 10.2. Despite star formation being mostly associated with disks, the dispersion of disk sSFR still increases with M\(^{*}\). We conclude that the presence of bulges/bars is likely responsible for the large dispersion of sSFR in massive SFGs, while low-mass SFGs are mostly disk dominated and thus have a small dispersion. Our results suggest that star formation on galactic scales is dramatically affected by central dense structures through both enhancing and/or quenching processes, while lower-mass SFGs tend to have less bursty SFHs. However, the dispersion of the sSFR becomes significantly smaller and remains constant when only disk-dominated SFGs are counted. This finding implies that the impact of stochastic stellar feedback on star formation is likely to follow the same pattern in all disk galaxies, showing no correlation with halo potential.

Key words: galaxies: evolution – galaxies: starburst – infrared: galaxies

1. INTRODUCTION

Star-forming galaxies (SFGs) exhibit a tight correlation between stellar mass (M\(^{*}\)) and star formation rate (SFR), i.e., the so-called star formation main sequence (SFMS), from early cosmic epochs to the present day (Elbaz et al. 2007; Noeske et al. 2007; Karim et al. 2011; Wuyts et al. 2011; Whitaker et al. 2012). This fundamental relationship has been widely used to test models of galaxy formation and evolution (e.g., Peng et al. 2010; Behroozi et al. 2013). While much progress has been made in understanding selection effects and uncertainties in SFR and M\(^{*}\) measurements (Kennicutt & Evans 2012; Renzini & Peng 2015), the measurements of the SFMS from different works based on multi-wavelength deep surveys surprisingly reached a good agreement when calibrated to the same standards (Speagle et al. 2014). Focus has now turned to characterizing the slope, dispersion, and normalization of the SFMS in detail, aimed at resolving the contributions of different physical processes regulating star formation on galaxy scales in a statistical sense.

The dispersion of the SFMS at fixed M\(^{*}\) measures the variation in the level of star formation among similarly massive galaxies. Measurement errors turn out to contribute little to the variation (Salmi et al. 2012), and the dispersion in specific SFR (sSFR = SFR/M\(^{*}\)) thus reflects the diversity in star formation histories (SFHs) and variability in SFRs on short timescales (Dutton et al. 2010; Sparre et al. 2015).

Multiple processes shape the SFH of a galaxy, including gas accretion, minor mergers, stellar feedback, and quasar/radio-mode feedback (see Moustakas et al. 2013 and reference therein). Relative roles of these processes are usually dependent on halo mass and cosmic epoch (Oser et al. 2010; Behroozi et al. 2013). In particular, stellar feedback is simulated to impact further star formation, leading to a larger fluctuation in SFRs on timescales of \(\sim 10^{7-8}\) years in lower-mass galaxies (Hopkins et al. 2014). However, this prediction is inconsistent with current observations. The dispersion of sSFR is reported to be constant (\(\sim 0.3\) dex) over a wide M\(^{*}\) range for z \(\sim 2\) SFGs (Rodighiero et al. 2011; Schreiber et al. 2015), but tends to be larger for more massive SFGs in the lower-redshift universe (Guo et al. 2013; see also Ilbert et al. 2015). SFR measurement for individual SFGs is critical in quantitatively studying the dependence of sSFR dispersion on M\(^{*}\). More efforts are required to determine what is responsible for the disagreement between theoretical and observational sides.

In this Letter, we examine the dependence of sSFR dispersion on M\(^{*}\) using a complete sample of local SFGs selected from the Sloan Digital Sky Survey (SDSS). In addition, the presence of non-star-forming bulges in SFGs may lower sSFR and increase sSFR dispersion. We take this effect into account in our examination. A Chabrier (2003) initial mass function (IMF) is used throughout this work.

2. SAMPLE AND DATA

We select a local sample of galaxies from SDSS data release 7 (Abazajian et al. 2009), which covers \(\sim 8000\) deg\(^{2}\) of the sky with spectroscopic observations nearly complete to r \(< 17.77\). It has become clear that H\(_{\alpha}\) + 22 \(\mu\)m is a robust SFR indicator with minimal scatter (\(\sim 0.14\) dex; Kennicutt et al. 2009; Hao et al. 2011; Lee et al. 2013), and the spread of SFRs is thus least influenced by the measurement errors. We therefore use the infrared (IR) 22 \(\mu\)m observations from the Wide-field Infrared Survey Explorer (WISE) all-sky survey, together with
Hα from SDSS, to measure SFRs on short timescales (∼10^7 years) compared to the indicator of ultraviolet (UV)+IR continuum luminosity that measures SFRs over scales of ∼10^8 years (Kennicutt & Evans 2012). The SDSS catalog is cross-correlated with the WISE all-sky survey catalog using a matching radius of 3", equal to half of the WISE beam size at 3.4 μm. Only the closest counterpart is chosen when multiple WISE sources are found within the radius. The WISE all-sky survey reaches a 5σ sensitivity of 0.08, 0.11, 1, and 6 mJy at 3.4, 4.5, 12, and 22 μm, respectively (Yan et al. 2013). We take 22 μm fluxes above the 3σ level (∼3.6 mJy) to estimate IR luminosity. This flux limit corresponds to an IR-based SFR of 0.1 M⊙ yr⁻¹ at redshift z = 0.03 when the IR spectral energy distribution (SED) of Chary & Elbaz (2001) is applied, according to the average SFR of 10⁰.⁵ M⊙ galaxies on local SFMS by Whitaker et al. (2012). Our sample is limited to 0.01 < z < 0.03 in order to collect a sufficiently large number of galaxies with 22 μm detection. The lower limit z = 0.01 is set to avoid serious fiber aperture effect (Hopkins et al. 2003; Lee et al. 2013). We adopt the photometric magnitudes in u, g, and r from the SDSS pipeline (Stoughton et al. 2002); optical emission line fluxes, rest-frame colors, and M8 from the MPA-JHU value-added galaxy catalogs (VAGCs; Tremonti et al. 2004); and Sérsic indices from the NYU value-added catalog (Blanton et al. 2005). The stellar mass in the VAGCs are derived from optical broadband SEDs. The SDSS limit of r < 17.77 for the main galaxy sample enables a complete selection for galaxies with log(M8/M⊙) ≥ 8.8 at z < 0.03. We convert IMF from Kroupa to Chabrier by dividing M8 by a factor of 1.06.

After removing duplicated objects and spectrally classified AGNs, we obtain 21,307 galaxies with log(M8/M⊙) ≥ 8.8 in 0.01 < z < 0.03 as our sample. Following Brinchmann et al. (2004), we correct fiber aperture effect for observed Hα fluxes. In practice, we use the relationships between the Hα equivalent width and u - g - r fiber colors to estimate Hα flux outside the fiber and obtain the total Hα flux of a galaxy. We test our aperture correction using a sample of SDSS galaxies at 0.05 < z < 0.1, for which fiber aperture effect is ignorable, finding an uncertainty of 0.2 dex for the total Hα flux to be independent of M8. We calculate SFR following Lee et al. (2013) as below:

$$\text{SFR} = 9.12 \times 10^{-9} (L_{\text{Hα}} + 0.034 L_{22})^{1.06},$$

where L22 is 22 μm monolithic luminosity. A factor of 1.7 is used to convert Salpeter into Chabrier IMF.

For 22 μm undetected galaxies, either quiescent ones or IR-faint SFGs mostly with log(M8/M⊙) < ∼9.5, SFR is estimated from Hα flux. The observed Hα flux is corrected for extinction, which is determined using the Balmer decrement with intrinsic Hα/Hβ = 2.86 and the extinction law of Cardelli et al. (1989; with Rv = 3.1 and coefficients updated by O'Donnell 1994). Then, the SFR is calculated using

$$\text{SFR} = 7.9 \times 10^{-42} L_{\text{Hα,corr}},$$

where L_{Hα,corr} is the extinction-corrected Hα luminosity. We note that 22 μm undetected galaxies are marginally affected by extinction, and the estimate of SFR from extinction-corrected Hα agrees perfectly with that from Hα+22 μm (Kennicutt & Evans 2012).

Figure 1 shows the distribution of all 21,307 sample galaxies in the M8−sSFR diagram. Quiescent galaxies are clearly separated from the main sequence of SFGs. We split sample galaxies into five mass bins over 10⁰.⁵−10¹⁰.⁸ M⊙ and select sSFR values in each bin where the number density reaches minimum as separation points between the populations. The best-fit line to the five separation points is shown in Figure 1. Galaxies above the line are classified as SFGs, yielding 17,807 SFGs to form an SFMS. Of them, 8036 are with log(M8/M⊙) > 9.5, of which 6004 (75%) have 22 μm detection. Below this mass cut, we adopt an SFR based on Hα for all SFGs because the 22 μm detection rate rapidly declines. We fit the SFMS and obtain the best fit as log(SFR) = (0.56 ± 0.02) × log(M8/10¹⁰ M⊙) − (0.47 ± 0.01).

It is necessary to decompose the central structure from the star-forming disk of a galaxy when we consider a “realistic” sSFR since classical bulges are generally red and dead (e.g., Drory & Fisher 2007). Following Bluck et al. (2014), each galaxy is assumed to consist of a classical bulge (n = 4) and an exponential disk (n = 1). Using the catalog of bulge+disk decompositions in g and r from Simard et al. (2011) together with the mean color−M8 relation from the VAGCs, we convert r-band bulge-to-total light ratio ((B/T)g) of a galaxy into bulge-to-total mass ratio (B/T) and estimate the stellar mass of the disk component (Mg) from M8. Our estimates of B/T are consistent with those based on resolved broadband SEDs (Mendel et al. 2014). A large fraction of SFGs with log(M8/M⊙) > 10.3 in our sample are not included in the bulge+disk decomposition catalog because of r > 14. We use a global Sérsic index to estimate B/T. Galaxies with a global Sérsic index n ≤ 1.5 are treated as disk galaxies with B/T = 0 and those with n ≥ 4 are usually elliptical galaxies with B/T = 1. The mean relation between B/T and n from the bulge+disk decomposition catalog is used to estimate B/T for galaxies with n between 1.5 and 4. Our sample SFGs with log(M8/M⊙) < 9.5 are mostly disk dominated with n < 1.5. By doing so, we obtain a disk stellar mass Mg for our sample SFGs. Considering that star formation is in general irrelevant to the classical bulge of a galaxy, we divide the total SFR by Mg to obtain the disk sSFR.
3. THE DISPERSION OF THE SFMS

Our sample of 17,807 SFGs form an SFMS at $z \sim 0.02$, best described by

$$\log(\text{sSFR}) = \alpha \times \log\left(\frac{M^*/10^{10.5} M_\odot}{10^{10.5} M_\odot}\right) + \beta$$

(3)

with $\alpha = -0.44$ and $\beta = -1.68$. Here, sSFR$_t$ is the total sSFR given in units of Gyr$^{-1}$. If the disk sSFR is adopted, then we obtain the best-fit SFMS with $\alpha = -0.32$ and $\beta = -1.42$. For the relation between the disk sSFR and $M^*_D$, the best-fit parameters are $\alpha = -0.35$ and $\beta = -1.54$. It is clear that the relation between the sSFR and $M^*$ remains substantially flattened when the disk sSFR is adopted. Still, the disks in more massive SFGs have on average a lower sSFR and thus a lower level of star formation activity in general.

We split SFGs of $10^{8.8-10.2} M_\odot$ into seven mass bins of width $= 0.2$ dex and two bins of $10^{10.2-10.5} M_\odot$ and $10^{10.5-11} M_\odot$. Fitting a normal distribution to the histogram of the sSFR in logarithm for each mass bin, we take $1\sigma$ of the best-fit profile as the sSFR dispersion ($\sigma_{\text{sSFR}}$) in units of dex. Figure 2 shows the sSFR dispersion as a function of $M^*$. It can be seen that the dispersion $\sigma_{\text{sSFR}}$ increases with $M^*$ from $0.36 \pm 0.01$ dex at $<10^{9.6} M_\odot$ to $0.51 \pm 0.02$ dex at $>10^{10.2} M_\odot$. In other words, more massive SFGs have a wider spread in sSFR. Similarly, the dispersion of the disk sSFR is also measured. As shown in Figure 2, the same increasing tendency is found for the dispersion of the disk sSFR at $\log(M^*/M_\odot) > 9.6$. At $\log(M^*/M_\odot) > 10.2$, the dispersion of the disk sSFR is indeed lower than that of the total sSFR, although uncertainties are large. It worth noting that the average disk sSFR is higher than the average total sSFR at $\log(M^*/M_\odot) > 10.2$, but the dispersion of the disk sSFR is smaller than that of the total sSFR for the same sub-population of SFGs. Accounting for measurement errors in $B/T$, the intrinsic dispersion in the disk sSFR would be even smaller merely at the high-mass end.

The best-fit log-normal profiles of sSFR distribution in three different mass bins are shown in the inner panel of Figure 2. The sSFR dispersion of SFGs with $\log(M^*/M_\odot) = 8.8-9.6$ is based on extinction-corrected H$\alpha$. We notice that the dispersion of H$\alpha$-based sSFR is slightly larger than that based on H$\alpha + 22 \mu m$. This discrepancy is likely due to the uncertainties in fiber aperture correction ($\sim 0.2$ dex), while WISE$22 \mu m$ observation is free from such uncertainties. Nevertheless, the dispersion of sSFR at the low-mass end with $\log(M^*/M_\odot) < 9.6$ remains substantially lower than that at $\log(M^*/M_\odot) > 10.2$. We note that for the mass bin $10^{10.5-11} M_\odot$, sSFR dispersion is somewhat broadened by the systematic change in the sSFR across the mass range, besides the increase of SFMS scatter itself. The latter stays at $\sim 0.51$ dex for $M^* > 10^{10.2} M_\odot$. Our estimate of the SFMS scatter appears high compared to those in previous works, likely due to the systematic uncertainties in fiber effect correction, and sample selection as the wide coverage in the IR (and SFR) enables a proper selection of SFGs in terms of sSFR.

We further examine sSFR dispersion as a function of disk mass $M^*_D$. For comparison, we select a sub-sample of disk-dominated SFGs from our sample of SFGs using the criteria $(B/T_i) < 0.2$ and $n_i < 1.5$. Similarly, subsamples of SFGs with $B/T > 0.3$ and $B/T < 0.3$ are drawn. For the disk-dominated SFGs, $M^*$ is equal to $M^*_D$. We split our SFG sample and the subsamples into the same nine mass bins in terms of $M^*_D$ and measure the sSFR dispersion. Figure 3 presents the sSFR dispersion as a function of $M^*_D$ for SFGs, disk-dominated SFGs, and SFGs with $B/T > 0.3$ and with $B/T < 0.3$, respectively. For the parent sample, dispersions in total sSFR and in disk sSFR are both calculated and shown. The comparison is limited to the four mass bins over $10^{9.6-10.5} M_\odot$, where the SFR is robustly estimated in a consistent way. The dashed (dotted) line represents the best-fit relation between the total (disk) sSFR dispersion and $M^*$ in Figure 2. For mass-selected SFGs grouped by $M^*_D$ (triangles), the dispersion of total sSFR is similar to that obtained in bins split by $M^*$, and the dispersion of disk sSFR is noticeably smaller than in the former disks with $M^*_D > 10^{10} M_\odot$. Surprisingly, the sSFR dispersion becomes substantially smaller and remains nearly constant (0.30 dex) over the mass range $10^{9.5-10.5} M_\odot$ when only disk-dominated SFGs are
counted. When splitting the parent sample of SFGs by $B/T$, disk sSFR dispersion shows a distinct separation between the two subsamples. We point out that the cut $B/T > 0.3$ selects the subsample of SFGs with $B/T$ and $M_*$ spreading over wide ranges; a smaller $M_D^*$ covers a wider range of $M_*$, thus with a larger dispersion in disk sSFR. Meanwhile, SFGs with $B/T < 0.3$ are close to disk-dominated SFGs with similar $M_*$ and are less affected by central bulges. We conclude that the mixture of the disks in SFGs with different $B/T$ and $M_*$ maximizes disk sSFR dispersion, while the dispersion is minimized when only pure disks are counted.

4. DISCUSSION AND CONCLUSION

Our results show that disk sSFR is generally higher than total sSFR when global star formation is linked to the disk component of SFGs. Differing from the finding of mass independence for disk sSFR by Abramson et al. (2014), we obtain the $M^*$-disk sSFR relation with a slope of $-0.32$, suggesting that disks in more massive SFGs have on average a lower level of star formation activity. A slope of $-0.35$ is obtained for the relation between disk sSFR and $M^*$. Quenching of star formation in SFGs involves processes of consuming gas within galaxies and shutting down gas accretion in halos. The latter is strongly dependent on halo mass (Woo et al. 2013) and may be associated with slow quenching processes (Fang et al. 2013; Peng et al. 2015). In such a framework, it is not surprising that disks in massive galaxies lack gas supply compared to low-mass SFGs, especially disk-dominated ones. On the other hand, massive SFGs tend to have a prominent central bulge (Bluck et al. 2014), which may stabilize gas in disks and suppress star formation (so-called morphology quenching; Martig et al. 2009). We therefore argue that the decline of star formation in disks of massive SFGs is a natural consequence of halo quenching and is probably affected by central bulges through AGN feedback or morphology quenching.

The most striking result from Figure 2 is that sSFR dispersion increases remarkably with $M_*$, from $q_{\text{sSFR}} = 0.37 \pm 0.01$ dex at $<10^{9.6} M_\odot$ to $0.51 \pm 0.02$ dex at $>10^{10.2} M_\odot$. An increase with $M_*$ is also found for disk sSFR dispersion. The mass dependence of sSFR dispersion has been seen in SFGs at $z \sim 0.7$ (Guo et al. 2013) and over a wide redshift range (Ilbert et al. 2015). Dispersion in sSFR traces SFH diversity and variation of SFRs in SFGs of similar $M_*$. Here, the SFH diversity refers to the SFR offset over timescales of $\sim 10^{5-9}$ years, and the variation in Hα-based SFR is on timescales of $\sim 10^7$ years. We argue that the increase of sSFR dispersion is governed by a mixture of physical processes regulating stochastic starbursts on short timescales and staged star formation on relatively long timescales. For massive SFGs, halo-driven processes are proposed to suppress gas accretion and drive massive SFGs leaving the SFMS slowly (Peng et al. 2015); secular processes (disk instabilities, bar-driven tidal disruption, minor mergers) and major mergers/interactions induce starbursts followed by strong stellar feedback afterward; central bulges influence star formation in SFGs via bulge-driven processes, and the scatter in $B/T$ for SFGs with similar $M_*$ contribute additional spread to the sSFR dispersion. In contrast, lower-mass SFGs are less affected by these processes and exhibit a smaller sSFR dispersion in general. In addition, low-mass satellite galaxies are more sensitive to environmental quenching (Peng et al. 2010). Since our sample is selected from a limited volume, the environmental effects on the sSFR dispersion are difficult to examine, leaving an open issue for future studies.

However, an sSFR estimate based on mid-IR emission might be significantly contributed to by the old stellar population in massive galaxies (Salim et al. 2009; Chang et al. 2015), diluting the significance of the increment of sSFR dispersion with $M_*$ that we found. Nevertheless, the dispersion of Hα-based sSFR is also confirmed to increase with $M_*$, having 0.55, 0.62, and 0.65 dex in the three mass bins over $10^{10-11} M_\odot$, respectively. These are much higher than the dispersions of Hα + 22 μm-based sSFR. The reasons for this discrepancy are unclear. We suspect that complex dust geometry could be one reason.

A remarkable discrepancy in the disk sSFR dispersion is found between the disk component of massive SFGs and morphology-limited disks (see Figure 3), although measurement errors in $B/T$ may slightly enlarge the dispersion for the former. The comparison of dispersion in disk sSFR between $B/T > 0.3$ and $B/T < 0.3$ reveals that a mixture of SFGs with $B/T$ and $M_*$ over wider ranges leads to a larger spread in disk sSFR. These again support that the existence of central bulges-bars enlarges the dispersion in disk sSFR. Interestingly, disk sSFR dispersion becomes substantially smaller and remains roughly constant over $9.6 < \log(M_*/M_\odot) < 10.5$ when disk-dominated SFGs are counted. The similarity of sSFR dispersion across $M_D^*$ for disk-limited SFGs is also seen at $z \sim 2$ (Salmi et al. 2012). This finding of mass independence of sSFR dispersion strongly suggests that star formation in pure disks is free from bulge-driven processes, following the same pattern of star formation at least over $9.6 < \log(M_*/M_\odot) < 10.5$. The similarity also implies that the mode of stochastic and bursty star formation in disk-dominated SFGs is unlikely correlated with halo potential. Our finding does not support the theoretical predictions in Hopkins et al. (2014) that sSFR dispersion rapidly increases with decreasing $M_*$ as stellar feedback plays an important role in driving a higher fraction of gas out of lower-mass galaxies and prevents further star formation. This conflict could be caused by the treatment of stellar feedback in simulations if a fixed fraction of total energy output is set to heat the interstellar medium (ISM). Stellar superwinds are often seen moving along the direction perpendicular to the disk plane of a starburst galaxy (e.g., M82) and might not strongly affect the ISM. The mass independence of sSFR dispersion in pure disks should be expected if the impact of stellar feedback on further star formation is negligible.

Our results suggest that the presence of central dense structures in massive SFGs has dramatic effects on galaxy-scale star formation, leaving not only the mean total/disk sSFR systematically lower but also the sSFR dispersion larger, compared to low-mass disk-dominated SFGs. Our finding of the mass independence of sSFR dispersion in pure disks indicates that disk galaxies of different $M_*$ obey the same mode of star formation, showing no correlation with halo potential.

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