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THE MASS-INDEPENDENCE OF SPECIFIC STAR FORMATION RATES IN GALACTIC DISKS

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ABSTRACT

The slope of the star formation rate/stellar mass relation (the SFR “Main Sequence”; SFR–M) is not quite unity: specific star formation rates (SFR/M) are weakly but significantly anti-correlated with M. Here we demonstrate that this trend may simply reflect the well-known increase in bulge mass-fractions—portions of a galaxy not forming stars—with M. Using a large set of bulge/disk decompositions and SFR estimates derived from the Sloan Digital Sky Survey, we show that re-normalizing SFR by disk stellar mass (sSFRdisk ≡ SFR/Mdisk) reduces the M dependence of SF efficiency by ~0.25 dex per dex, erasing it entirely in some subsamples. Quantitatively, we find log sSFRdisk–log M to have a slope βdisk ≈ −0.07 ± 0.04 (depending on the SFR estimator and Main Sequence definition) for star-forming galaxies with M ≳ 1010 M⊙ and bulge mass-fractions B/T ≲ 0.6, generally consistent with a pure-disk control sample (βcontrol = −0.05 ± 0.04). That (SFR/Mdisk) is (largely) independent of host mass for star-forming disks has strong implications for aspects of galaxy evolution inferred from any SFR–M relation, including manifestations of “mass quenching” (bulge growth), factors shaping the star-forming stellar mass function (uniform d log M/ dt for low-mass, disk-dominated galaxies), and diversity in star formation histories (dispersion in SFR(M, t)). Our results emphasize the need to treat galaxies as composite systems—not integrated masses—in observational and theoretical work.

Key word: galaxies: evolution

Online-only material: color figures

1. INTRODUCTION

The observation of a correlation between galaxy star formation rates (SFRs) and stellar masses (M) has generated considerable interest. Seen from z = 0 to z > 2 (e.g., Brinchmann et al. 2004; Daddi et al. 2007; Wuyts et al. 2011; Guo et al. 2012), the MS broadly reproducible in cosmological simulations (Kereš et al. 2005; Neistein & Dekel 2008; Lagos et al. 2011; Hopkins et al. 2013) and actively employed as a basis/constraint for evolutionary models (Peng et al. 2010; Leitner 2012; Behroozi et al. 2013), understanding such details is increasingly important.

Here we reinterpret the slope of the MS.

The MS is conveniently recast in terms of galaxies’ specific star formation rates—sSFR ≡ SFR/M—or fractional mass growth per unit time. If constant, sSFR is the (inverse) M e-folding timescale.

The M dependence of sSFR—the departure of the MS slope from unity—contains information about the “efficiency” of SF across the galaxy mass spectrum. Typically, it is parameterized by the power-law index:

$$\beta \equiv \frac{d \log \text{sSFR}}{d \log M}.$$

If all galaxies formed stars with equal efficiency, β would be identically zero. Observationally, β appears close to zero, permitting convenient approximations in evolutionary models (e.g., Peng et al. 2010); sSFR(t) is nearly independent of mass, so the entire star-forming population is nearly describable by a single number (absent significant dispersion at fixed M; see Section 6).

Yet, β is not zero. Many studies using SFR indicators from the UV through the radio have concluded that, above 1010 M⊙, −0.6 ≤ β ≤ −0.1 for z ≲ 2 (Brinchmann et al. 2004; Salim et al. 2007; Karim et al. 2011; Whitaker et al. 2012, but cf. Pannella et al. 2009). Peng et al. (2010) and Whitaker et al. (2012) find β ≃ 0 for blue galaxies (see Section 5 below), but that β is significantly negative for the global star-forming population seems secure.

More direct definitions of “SF efficiency” relate SFR to a gas mass, but sSFR is an efficiency metric.
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### 2. DATA

We use data from the Seventh SDSS Data Release (DR7; Abazajian et al. 2009), drawing SFRs and $M_*$ from Brinchmann et al. (2004, hereafter B04),6 and two-dimensional bulge/disk decompositions from Simard et al. (2011, hereafter S11). Given their extensive past use, we also analyze DR4-based B04 SFRs—calculated using a different procedure—in parallel. Below, B04 and B047 refer respectively to DR4-/DR7-based measurements while “B04” refers to the original paper (B04; lacks a stand-alone reference at present).

Both SFR and $M_*$ assume a Kroupa (2001) initial mass function. B04 give these quantities as probability distributions. We adopt the median total values, but results are unchanged if the mean or mode is used instead.

Below, quantities describing disks are denoted by the (additional) subscript "disk." Quantities lacking this tag describe global galaxy properties. Table 1 lists all parameters and their sources; $(H_0, \Omega_m, \Omega_\Lambda) = (70 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.3, 0.7)$ is assumed everywhere.

#### 2.1. Bulge/Disk Decompositions

We use S11 “fixed $n_b$” fits, where $n_b \equiv 4$ is the Sérsic index of the bulge component. These are appropriate for almost all sources (S11, Section 4.2), but results are qualitatively unaffected if the “free $n_b$” models are used instead. We take disk and total $g, r$ absolute magnitudes from the fits. Employing model-independent Petrosian magnitudes from the NYU Value Added Galaxy Catalog (Blanton et al. 2005) does little but reduce $M_{*,\text{disk}}$ for blue disks (Section 4).

To avoid dust and S/N effects, we limit our analysis to face-on galaxies $(b/a \geq 0.8)$ with well-measured disk fluxes $(\text{Err}(g, r)_{\text{disk}} \leq 0.05)$ and total masses $(M_* \geq 10^9 M_\odot)$. We further restrict the MS samples (see Section 3) to galaxies requiring a two-component bulge+disk model.8 Relaxing these cuts affects $\beta_{\text{disk}}$ less than other systematics, but employing them ensures maximally accurate $M_{*,\text{disk}},$ SFR, and meaningful $M_{*,\text{disk}}$ corrections.

#### 2.2. The Sample

In total, 12,669 systems common to DR4/DR7 meet these criteria, with median $(z, M_*) = (0.08, 5.5 \times 10^{10} M_\odot)$. These

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### Table 1

| Quantity | Unit | Source* | Definition |
|----------|------|---------|------------|
| $r_{\text{disk}}$ | SDSS magb | 1 | Disk absolute $r$ magnitude $k$-corrected to $z = 0.1$ |
| $(g - r)_{\text{disk}}$ | SDSS magb | 1 | (Disk) rest-frame color $k$-corrected to $z = 0.1$ |
| $z$ | ... | 1 | Galaxy redshift |
| $n_{\text{Sérsic}}$ | ... | 1 | Global $r$-band Sérsic index |
| $b/a$ | ... | 1 | Global $r$-band axis ratio $(1-\text{ellipticity})$ |
| $M_{*,\text{disk}}$ | $M_\odot$ | 2(3) | (Disk) stellar mass |
| $\text{SFR}$ | $M_\odot$ yr$^{-1}$ | 2 | Aperture-corrected star formation rate (median of PDF) |
| $\text{sSFR}$ | yr$^{-1}$ | 2 | Galaxy specific star formation rate (SFR/$M_*$) |
| $\text{sSFR}_{\text{disk}}$ | yr$^{-1}$ | 3 | Disk-mass-normalized star formation rate (SFR/$M_{*,\text{disk}}$) |

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Notes.

a (1) S11; (2) B04$^4$/B04$^7$; (3) derived.

b AB system offsets are $<0.01$ mag.

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The implication of $\beta < 0$ is that low-mass galaxies grow (logarithmically) faster than higher-mass contemporaries. Interesting on its own, this fact is important also because $\beta$ informs two other key questions: Why has the shape of the star-forming stellar mass function remained unchanged since $z \sim 2$ (e.g., Ilbert et al. 2010; Tomczak et al. 2014)? What stops SF?

Setting aside the mass function for now (see Section 5 and the extensive treatment of Peng et al. 2010) the question of what stops SF in galaxies nicely illustrates $\beta$’s influence on MS-based evolutionary models.

In the $\beta \rightarrow 0$ limit, galaxy evolution is binary: systems are either star-forming—growing in lock-step with all other such objects—or not. An implication is that mechanisms taking galaxies from the first population into the second act quickly and operate across all $M_*$. Conversely, if $\beta$ is substantially negative (as is likely), galaxy evolution is more nuanced. A galaxy’s global SF efficiency changes as it grows, gradually falling to perhaps negligible levels with time. “Quenching” is thus a mix of processes pulling systems vertically off the MS and lowering sSFRs as they move along it ($\beta$ reflects the latter).

Many mechanisms have been proposed that implicitly or explicitly account for mass-dependent sSFRs, including virial-heating of the circumgalactic medium by dark matter halos (inducing “hot-mode” accretion) and active galactic nuclei (AGNs; e.g., Dekel & Birnboim 2004; Kereš et al. 2005; Croton & Farrar 2008; van de Voort et al. 2011). Such processes may be at work, but they are not directly coupled to the observables in sSFR$-M_*$, so hypotheses are complicated by uncertainties in linking these phenomena.

Indeed, observationally, there is a deeper concern. sSFR = SFR/$M_*$ (hence $\beta$) is biased, prima facie, as a description of SF as the numerator has essentially nothing to do with a significant part of the denominator—the bulge. The well-known correlation of bulge mass fractions, $B/T$, with $M_*$, $\beta < 0$ is expected simply because ever smaller portions of a galaxy participate in SF, independent of the nature of the SF itself.

If sSFR$-M_*$ is to add meaningfully to our knowledge of galaxy evolution, at a minimum, the extent to which $\beta$ reflects changes in the quality of SF (how) versus the proportion of a galaxy contributing to it (where) must be understood. Large spectrophotometric surveys—such as the Sloan Digital Sky Survey (SDSS; York et al. 2000)—enable this.

Below, we demonstrate the importance of recognizing where SF occurs, showing that most-to-all of $\beta$ can be erased simply by redefining “sSFR” using the mass in galactic disks.

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### Notes.

6 http://www.mpa-garching.mpg.de/SDSS/DR7/sfrs.html
7 Known to overestimate SFR in quiescent galaxies; http://www.mpa-garching.mpg.de/SDSS/DR4/Data/sfr_catalogue.html.
8 $P$(NOT 2-component) < 0.32; S11, Section 4.2.1.
include: “pure-SF” (42%); “SF/AGN composite” (9%); “AGN” (6%); “LINER” (15%); and “unclassifiable” galaxies (no detected emission; 28%).

Given the SDSS spectroscopic limit, this sample is roughly complete to $4 \times 10^{10} M_\odot$ for star-forming systems (assuming 90th percentile color and redshift). However, SFR completeness—set by line flux, spectral S/N, and broadband colors—is of greater concern since it can distort fits in the sSFR–$M_\star$ plane. Since photometric completeness is not an issue and $M_\star \approx 0.1$,$M_\odot$ yr$^{-1}$ is well-measured by B04, the data should be relatively unbiased above the corresponding MS mass, $M_\star \approx 10^{10} M_\odot$. We perform all fits above this limit and derive statistics using $1/V_{\text{max}}$ weighting.

Typical half-light radii are $3\times 8''$. As $\text{FWHM}_{\text{SDSS}} \approx 1/4$, disks should be well-resolved.

2.3. Calculation of Disk Masses

We estimate $M_\star,\text{disk}$ empirically. First, we select a sample of disk-dominated systems—bulge-to-total flux ratio ($B/T_r) \leq 0.2$—whose color and mass should largely reflect those of pure disks. We then calculate $r$-band mass-to-light ratios, $\Upsilon_r \equiv M_r/L_r$, and derive $(\log \Upsilon_r, (g-r))$ by fitting a second-order polynomial. We do this independently for B04$_4$ ($M_\star$ from spectral fitting by Kauffmann et al. 2003) and B04$_7$ ($M_\star$ from photometric fitting). B04$_7$ yields $(\log \Upsilon_r, (g-r)) = -1.00+2.47(g-r)-0.85(g-r)^2$, with B04$_4$ offsets $\leq 0.06$ dex for $g-r < 0.71$ (90th percentile disk color). Using $g$, $r$ absolute disk magnitudes:

$$\log M_\star,\text{disk}/M_\odot = -0.4(r_{\text{disk}} - r_\odot) + (\log \Upsilon_r, (g-r)_{\text{disk}}), \tag{2}$$

where $r_\odot = 4.64$ (Blanton & Roweis 2007).

We then define

$$\text{sSFR}_{\text{disk}} \equiv \text{SFR}/M_\star,\text{disk}. \tag{3}$$

This may not formally correspond to “the sSFR of the disk” as bulge/nuclear regions may contribute some SF, but to ease discussion and because such contributions should be small, we use “sSFR$_{\text{disk}}$” instead of “$M_\star,\text{disk}$-normalized SFR” below.

Figure 1 summarizes our analysis. Here we plot fits to the MS in both log sSFR–log $M_\star$ (left) and log sSFR$_{\text{disk}}$–log $M_\star$ space (right). Because the locus has no formal definition, we approximate the MS in five (non-independent) ways:

1. MS-ALL. All galaxies with sSFR above MS–3$\sigma$ (defined using B04$_4$).
2. MS-NOAGN. The same, excluding AGN, composite, and LINER galaxies.
3. PURE-SF. All pure-SF systems regardless of sSFR; excludes AGN-contaminated and unclassified galaxies.
4. BLUE DISK. All galaxies with $(g-r)_{\text{disk}} \leq 0.6$ regardless of spectral type or sSFR.
5. MS-SUPER. Intersection of all of the above; the purest, but smallest, sample.

Also overplotted are results for a “pure-disk control” sample (where $\text{sSFR} = \text{sSFR}_{\text{disk}}$) composed of pure-SF systems well-fit by a single-disk profile.$^9$

Three points are clear:

1. The slope, $\beta$, of sSFR–$M_\star$ is substantially steeper for the MS samples than for the pure-disk control (Figures 1(a) and (c));
2. The slope, $\beta_{\text{control}}$, of the pure-disk control is consistent with zero at the 1$\sigma$ to 2$\sigma$ level (as seen at $z \approx 1$ by Salmi et al. 2012);

Figure 1: MS fits before/after $M_\star,\text{disk}$ re-normalization (left/right) using B04$_4$/B04$_7$ data (top/bottom). SFR/$M_\star$– and SFR/$M_\star,\text{disk}$– have slopes $\beta$ and $\beta_{\text{disk}}$, respectively. Pure-disk control SFR/$M_\star,\text{disk}$– is also plotted (blue hatching). Gray denotes regions of possible sSFR bias; only data at $10^{10} M_\odot \leq M_\star \leq 2 \times M_{\text{SFG}}^0$ (the 90th percentile for pure-SF galaxies) were fit. Band widths denote 1$\sigma$ uncertainties.

(A color version of this figure is available in the online journal.)

$^9$ $P$ (NOT 2-component) $\geq 0.5$, $\sigma_{\text{Sectic}} \leq 2$
3. After $M_{\text{ disk}}$ re-normalization, MS slopes, $\beta_{\text{ disk}}$, and intercepts are similar to—even consistent with—those of the pure-disk controls (Figures 1(b) and (d)).

Quantitatively, we find $-0.43 \leq \beta \leq -0.24$ (consistent with results from Salim et al. 2007; Karim et al. 2011; Whitaker et al. 2012), but $-0.20 \leq \beta_{\text{ disk}} \leq 0.00$. (Spreads reflect data set and intersample variations.) This $\sim 0.25$ dex per dex enhancement is interesting in an absolute sense: it is substantial (perhaps entirely) homogenizes mean SF efficiencies over more than a factor of 10 in $M_\ast$. But, it is the homogenization of galaxies spanning $0.1 \lesssim B/T \lesssim 0.6$ with pure disks ($\beta_{\text{ control}} = -0.05 \pm 0.04$) that suggests $M_{\ast,\text{ disk}}$ re-normalization is physically meaningful.

Statistical uncertainties in $\beta$ and $\beta_{\text{ disk}}$ are $\sim 0.02$, derived from fits to 100 bootstrap resamplings of the data at $10^{10} M_\odot \lesssim M_\ast \lesssim 2 \times 10^{10} M_\odot$ (90th percentile $M_\ast$ for pure-SF galaxies). Systematics are clearly dominant, with MS definition and SFR estimate both contributing at the $\Delta \beta_{\text{ disk}} \approx 0.06-0.10$ level (Section 4).

Figure 2 shows the data. Gray points represent all galaxies, black the MS-SUPER sample, constituting $\sim 60\%$ of the SFR density in the local universe (MS-ALL comprises $\sim 90\%$). Two additional points are illustrated here: (1) Dispersion in the MS, $\sigma_{\text{MS}}$, is substantial; (2) Pure disks move from the top of the sSFR–$M_\ast$ relation to the middle of $s\text{SFR}_{\text{ disk}}$–$M_\ast$. We discuss $\sigma_{\text{MS}}$ in Section 6, but (2) is further evidence that the $M_{\ast,\text{ disk}}$ correction is physically meaningful: not only is $\beta$ pushed close to $\beta_{\text{ control}}$, but the original MS distribution is made to coincide with that of pure disks. Visually comparing the $1\sigma$ control spread (dashed blue lines) to that of $s\text{SFR}_{\text{ disk}}(M_\ast)$ emphasizes this point.

In sum, re-normalizing SFR by $M_{\ast,\text{ disk}}$ substantially (perhaps entirely) homogenizes SF efficiency in giant galaxies, placing bulge-dominated, $10^{11} M_\odot$ systems near the level of pure disks one-tenth as massive.

4. SYSTEMATICS

Once the MS is defined—its $\Delta \beta_{\text{ disk}} \sim 0.1$ effect (Figure 1)—two systematics affect $\beta_{\text{ disk}}$: $M_{\ast,\text{ disk}}$ calculation and SFR estimation.

$M_{\ast,\text{ disk}}$ is affected by bulge/disk decomposition and $\Upsilon_\ast$ calibration. Using B044 or B047 masses to calibrate $\Upsilon_\ast$ has an effect comparable to statistical uncertainties. Adopting $\Upsilon_\ast(g-r)$ from Bell et al. (2003) changes $\beta_{\text{ disk}}$ similarly, but can boost $\beta$, $\beta_{\text{ control}}$ by $\sim 0.1$ (B047 SFRs). Using Petrosian magnitudes can induce $\Delta \beta_{\text{ disk}} = 0.08$ (both data sets), but only for the BLUE DISK (and thus MS-SUPER) samples. Comparing S11-based $M_{\ast,\text{ disk}}$ to estimates derived from decompositions by Gadotti (2009; SDSS-based, but more complex than S11; $N_{\text{ gals}} = 529$) or Allen et al. (2006; fit to independent Millennium Galaxy Catalogue imaging (Liske et al. 2003); $N_{\text{ gals}} = 770$), we find no trends larger than the scatter ($\sim 0.25$ dex) at $M_\ast \gtrsim 10^{10} M_\odot$.

Hence, SFR systematics likely drive uncertainty in $\beta_{\text{ disk}}$.

Figures 2(a) and (c) illustrate this. The (substantial) changes between B044 and B047—bi-modality at high mass, increased dispersion—mainly reflect revised aperture corrections introduced after Salim et al. (2007) found B044 to overestimate sSFR in quiescent galaxies. Using a common $M_{\ast,\text{ disk}}$, we find $\Delta \beta(B044 \rightarrow B047) \approx 0.10$ for all MS samples. Swapping B04 SFRs for optical emission line estimates from the Padova-Millennium Galaxy and Group Catalogue (PM2GC; Calvi et al. 2011, requiring no color-based corrections), we find $\beta_{\text{ disk}}(\text{PM2GC}) = -0.18 \pm 0.08$ for galaxies with $(g-r)_{\text{ disk}} \lesssim 0.6$, consistent with the analogous $\beta_{\text{ disk}}$ obtained from B047. Hence, given the B044/B047 offsets, systematics in $\beta_{\text{ disk}}$ are likely $\sim 0.1$ once the MS is defined.
5. IMPLICATIONS

We have identified a quantity that is roughly constant for star-forming galaxies at $M_\ast \gg 10^{10} M_\odot$: SFR/$M_\ast$,disk. This implies that SF efficiency in the disks of star-forming galaxies (even bulge-dominated ones) is largely independent of global galaxy properties (e.g., halo mass). This is qualitatively different from (if anticipated by) findings regarding uniform SFR/$M_\ast$ in disk-dominated galaxies (Salmi et al. 2012), blue galaxies (likely because they are disk-dominated; see Section 1), and the correlation of $B/T$ with position on the MS (Martig et al. 2009; Williams et al. 2010; Lang et al. 2014; Omand et al. 2014), which our measurement of $\beta_{\text{contour}} \cong 0$ supports.

Indeed, our results suggest that the suppression of SF efficiency with $M_\ast$ due to bulge-growth is mostly superficial, caused by the association of “SF efficiency” with sSFR and the conflation of where and how SF occurs. That is, a key aspect of mass-quenching” is “bulge-building,” distinct from processes affecting SF where it occurs. In this we echo Kennicutt et al. (1994).

Whether bulge-growth is predominantly secular (converting dynamically “cold” disk material through, e.g., bar-instabilities; Kormendy & Kennicutt 2004) or merger-driven (adding “hot” dynamically “cold” disk material through, e.g., bar-instabilities; affecting SF where it occurs. In this we echo Kennicutt et al. “mass-quenching” is “bulge building,” distinct from processes affecting SF where it occurs. In this we echo Kennicutt et al. (1994).

A third implication is worth noting. Since $z \approx 2$, the low-$M_\ast$ slope of the star-forming stellar mass function has remained constant at $a \approx -1.4$, yet $\beta < 0$ is reported over the same interval almost universally (see Section 1 for references). These are inconsistent observations: $\beta < 0$ implies $a$ should steepen (dramatically) with time. Our results suggest that, at $M_\ast \approx 10^{10} M_\odot$ (where it is measured at $z > 0$), $\beta$ largely reflects $B/T$. Extrapolations from this regime to lower $M_\ast$—where star-forming galaxies are bulgeless—may thus be inappropriate. If in fact $\beta \rightarrow 0$ at lower mass—as results from Salim et al. (2007), Karim et al. (2011), and Whitaker et al. (2012) also hint—the MS and $a$ would be reconciled.

6. THE WIDTH OF THE SFR MAIN SEQUENCE

So far, we have neglected dispersion in the MS, $\sigma_{\text{MS}}$. Given B04 data, this appears reasonable: $\sigma_{\text{MS}} \lesssim 0.3$ dex, consistent with formal errors (Figure 2). However, B04 and numerous other data sets (e.g., Salim et al. 2007; Oemler et al. 2013; PM2GC) suggest $\sigma_{\text{MS}} \sim 0.4$–0.6 dex (peak-to-peak $\Delta$SFR($M_\ast$) $\gtrsim 1$ order of magnitude), implying that the width of the MS is qualitatively and quantitatively important.

Qualitatively, since $\beta_{\text{disk}} \approx 0$, $\sigma_{\text{MS}} > 0$ is necessary to preserve diversity in star formation histories (SFHs) as independently suggested by, e.g., stellar population synthesis (Poggianti et al. 2013; at least when $M_\ast(t) \approx M_{\text{disk}}(t)$). Comparing Peng et al. (2010, Figure 19) with Gladders et al. (2013, Figure 2) reveals the contrast between ($\beta$, $\sigma_{\text{MS}}$) = (0, 0) and $\neq$ (0, 0), respectively, in terms of SFH diversity.

Inversely, real dispersion quantitatively complicates the determination of SFHs based on MS evolution (Section 1): one must model $\sigma_{\text{MS}}(M_\ast, t)$. How this could be done is unclear; data are scant at $M_\ast \ll 10^{10} M_\odot$ and $z \gg 1$—key parameter space when modeling Milky Way analogs—and local measurements suggest $\sigma_{\text{MS}}$ (and therefore its navigation) only becomes more important in this mass regime (Salim et al. 2007, Section 7.5).

Regardless, assuming it can be precisely measured, interpreting $\sigma_{\text{MS}}$ will remain a challenge. Different SFR indicators probe different timescales ($\sim 10^7$ versus $10^8$–$10^9$ yr for optical and UV/IR metrics, respectively), so ambiguity in the causes of $\sigma_{\text{MS}}(t)$—e.g., minor mergers/starbursts (Dressler et al. 2013; Abramson et al. 2013), extended periods of enhanced gas accretion, stochasticity—and thus its relevance to the “fundamental” $M_\ast$ history of galaxies may persist. If so, the utility of the MS as a model for individual systems will remain questionable.

One can always imagine the opposite, however. If $\sigma_{\text{MS}}$ is “truly” small (e.g., Salim et al. 2012), our results suggest a quasi-identical SFH for all galactic disks (up to a scaling), with global galaxy-to-galaxy variations coming from bulge-building or environmental developments. Future spatially resolved spectroscopic studies of galaxies at all redshifts could shed substantial light on this issue.

In sum, the “$M_{\text{disk}}$ correction” is surely not the end of the story. Though it homogenizes star-forming disks in hosts with a range in $B/T$—placing, e.g., M31 and M33 on more similar footing—quenched disks exist at all $M_\ast$ which cannot be brought onto (some variant of) the MS. Other factors—bars, disk dynamics, halo heating, AGN activity, environment—must help pull these systems off the (flat) ridge line defined by normal disks; the key point is that these processes may manifest themselves in the dispersion and not the slope of the MS.

7. SUMMARY

Re-normalizing SFR by disk stellar mass, $M_{\ast,\text{disk}}$ can account for $\sim 0.25$ dex of declining sSFR per decade $M_\ast$, essentially removing the dependence of SF efficiency on galaxy mass for star-forming systems with blue disks (if not all star-forming galaxies). Besides suggesting that a key part of “mass quenching” is “bulge building”—distinct from processes affecting SF in disks—our findings ease tension between the MS and the evolution of the stellar mass function, and reinforce two important points:

1. “Understanding galaxy evolution demands the routine bulge–disk decomposition of the giant galaxy population at all redshifts” (Allen et al. 2006).

2. Dispersion in SFR($M_\ast$) likely reflects real diversity in SFHs and should not be ignored.

Upcoming IFU surveys (e.g., MaNGA; http://www.sdss3.org/future/manga.php) may constrain intrinsic spreads in SFR($M_{\ast,\text{disk}}$) and thus mechanisms shaping SFHs. Regardless, SFR/$M_{\ast,\text{disk}}$=$M_\ast$ and $B/T$=$M_\ast$ should serve as benchmarks for future theoretical models of galaxy evolution.

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