SDSS-IV MaNGA: A Star Formation–Baryonic Mass Relation at Kiloparsec Scales

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Abstract

Star formation rate density, \( \Sigma_{\text{SFR}} \), has shown a remarkable correlation with both components of the baryonic mass kiloparsec scales (i.e., the stellar mass density and molecular gas mass density, \( \Sigma_\star \) and \( \Sigma_{\text{mol}} \), respectively) for galaxies in the nearby universe. In this study, we propose an empirical relation between \( \Sigma_{\text{SFR}} \) and the baryonic mass surface density (\( \Sigma_b = \Sigma_{\text{mol,Av}} + \Sigma_\star \), where \( \Sigma_{\text{mol,Av}} \) is the molecular gas derived from the optical extinction, \( A_V \)) at kiloparsec scales using the spatially resolved properties of the MaNGA survey, the largest sample of galaxies observed via integral field spectroscopy (~8400 objects). We find that \( \Sigma_{\text{SFR}} \) tightly correlates with \( \Sigma_b \). Furthermore, we derive an empirical relation between \( \Sigma_{\text{SFR}} \) and a second-degree polynomial of \( \Sigma_b \), yielding a one-to-one relation between these two observables. Both \( \Sigma_b \) and its polynomial form show a stronger correlation and smaller scatter with respect to \( \Sigma_{\text{SFR}} \) than the relations derived using the individual components of \( \Sigma_b \). Our results suggest that these three parameters are indeed physically correlated, suggesting a scenario in which the two components of the baryonic mass regulate the star formation activity at kiloparsec scales.

1. Introduction

Understanding what the physical scenarios are that describe the star formation activity in galaxies is fundamental to explaining their evolution throughout their lifetimes. In turn, depending on the explored spatial scale, there have been mainly two different yet complementary scenarios that explain the star formation in galaxies. Broadly speaking, one possibility is that the number of newly formed stars in a galaxy is set primarily by the local amount of cold gas available to create that newly born population. On the other hand, star formation can also be affected by global properties, for instance, the dynamical structure of the disk of the galaxy as a whole (Kennicutt & Evans 2012, and references therein). A complementary approach suggests that star formation is self-regulated (e.g., Dopita 1985; Dopita & Ryder 1994; Silk 1997; Ostriker et al. 2010). In this scenario, momentum injection from massive stars balances the hydrostatic pressure due to the disk’s weight.

Observationally, empirical scaling relations have been fundamental to exploring the role of the baryonic mass in the physical processes that yield the number of newly born stars in the universe. The Schmidt–Kennicutt (SK) relation is the most well known of those relations. It provides a strong correlation between the observed star formation rate (SFR) and the amount of cold gas (Schmidt 1959; Kennicutt 1998). When using intensive measurements (i.e., properties average across a certain area projected in the sky), the SK relation (\( \Sigma_{\text{SFR}} vs. \Sigma_{\text{gas}} \)) follows a similar slope across several orders of magnitude, including a wide range of galaxy morphologies and types for normal star-forming galaxies (Gao & Solomon 2004). It can vary when exploring extreme starburst galaxies or galaxies at high redshift (e.g., Daddi et al. 2010; Genzel et al. 2010). Thanks to radio-interferometric surveys, there is also a wealth of data indicating that the SK relation is also valid at kiloparsec scales for a large sample of extragalactic star-forming sources (e.g., the HERACLES, THINGS, and EDGE-CALIFA surveys; Leroy et al. 2008; Walter et al. 2008; Bolatto et al. 2017). At a very first order, the SK law and its counterpart at kiloparsec scales, the resolved SK relation (rSK), can be described by the first scenario described above.

Another star-forming scaling relation is the one that shows a tight correlation between the galaxy-integrated SFR and the total stellar mass \( (M_\star) \). The so-called star formation main sequence (SFMS) has been derived for thousands of galaxies included in the DR7 Sloan Digital Sky Survey (SDSS; e.g., Kauffmann et al. 2003; Brinchmann et al. 2004). Note that in the SFR–\( M_\star \) plane, one can also observe a cloud of massive galaxies with little SFR (known as the retired sequence of galaxies). In the last decade, thanks to integral field unit (IFU) observations in large samples of galaxies, it has been possible to determine the existence of a local counterpart of the SFMS, the resolved SFMS (rSFMS; \( \Sigma_{\text{SFR}} \) versus \( \Sigma_\star \)), for a large sample of galaxies (Sánchez et al. 2013; Wynts et al. 2013). The existence of the rSFMS—as well as the spatially resolved

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version of the retired sequence—may also indicate a more intimate correlation between current star formation and the star formation history (SFH) of a galaxy at kiloparsec scales (e.g., Cano-Díaz et al. 2016). Recently, with large IFU data sets and the combination with direct observations of spatially resolved molecular gas, different studies have established that $\Sigma_{\text{SFR}}$ is mainly correlated to $\Sigma_*$, rather than $\Sigma_{\text{gas}}$ (e.g., Dey et al. 2019; Bluck et al. 2020). Similar studies have also noted the significant relation at kiloparsec scales between the molecular gas mass density and the stellar mass density (e.g., Lin et al. 2019; Barrera-Ballesteros et al. 2020).

The above two star-forming relations are not the only ones that correlate the $\Sigma_{\text{SFR}}$ with the baryonic mass component in galaxies at kiloparsec scales. Different authors have explored the relation between the $\Sigma_{\text{SFR}}$ and the $\Sigma_{\text{gas}}$ $\Sigma_*$ product or similar relations with the baryonic mass (e.g., Matteucci et al. 1989; Shi et al. 2011, 2018). Since the combination of baryonic densities scales with the disk hydrostatic midplane pressure, these studies were aimed at exploring whether star formation follows a self-regulated scenario. In this scenario, star formation is locally regulated by the interplay between the midplane pressure produced by the baryonic mass and the momentum flux due to supernova explosions from the most massive stars (Ostriker et al. 2010; Shetty & Ostriker 2012; Kim et al. 2013).

Despite the great advances in our understanding of star formation from these works, there has been a lack of systematic studies exploring the relation between the baryonic mass ($\Sigma_ = \Sigma_ + \Sigma_{\text{gas}}$) and $\Sigma_{\text{SFR}}$ at kiloparsec scales. Such a relation can shed some light regarding the most likely physical scenario of star formation at kiloparsec scales. In this study, we take advantage of the SDSS-IV MaNGA survey (Bundy et al. 2015), the largest IFU data set to date to explore this correlation. Furthermore, we also investigate the impact of a correlation of $\Sigma_{\text{gas}}$ with a nonlinear combination of $\Sigma_$. This paper is structured as follows. In Section 2, we present our sample selection, as well as an overview of the main features of the data cube for each galaxy included in the MaNGA survey. In Section 3, we show the observables derived from the data cubes required for this study and our main results, while in Section 4, we discuss our main findings. The main conclusions of this paper are presented in Section 5.

### 2. Sample and Data Cubes

The galaxies selected for this study are drawn from the latest sample of targets observed in the MaNGA survey (Bundy et al. 2015), which is part of the fourth generation of the SDSS-IV (Blanton et al. 2017). This sample includes galaxies observed from 2014 March to 2019 September (8405 data cubes). This sample corresponds to the internal release within the collaboration, also known as the MaNGA product launch (MPL-9). The MaNGA survey has been designed to obtain integral field spectroscopy (IFS) observations of more than 10,000 galaxies. A detailed description of the selection criteria for this survey is presented in Wake et al. (2017).

The observations of the MaNGA survey are taking place at the Apache Point Observatory using its 2.5 m telescope (Gunn et al. 2006). A detailed description of the instrumentation of the survey can be found in Drory et al. (2015). For a detailed explanation of the data strategy, the reader is referred to Law et al. (2016). The MaNGA reduction pipeline includes wavelength calibration, corrections from fiber-to-fiber transmission, subtraction of the sky spectrum, and flux calibration (Yan et al. 2016). The final product is a data cube with $x$- and $y$-coordinates corresponding to the sky coordinates, and the $z$-axis corresponds to the wavelength. Its final spaxel size is $0.5''$ with a spatial resolution of $2''$, corresponding to a mean physical scale of $\sim2$ kpc.

### 3. Analysis and Results

#### 3.1. Spatially Resolved and Integrated Properties from the Observed Galaxies

The local observables for this study are determined by applying the PIPE3D analysis pipeline to the MaNGA data cubes. A full description of this pipeline and its stellar and emission line fitting, uncertainty estimations, and derivation of physical properties can be found in Sánchez et al. (2016). An overview of how the two-dimensional distributions of stellar and gas components are derived for MaNGA data can be found in Barrera-Ballesteros et al. (2016, 2018). In particular, for this study, we use the stellar surface mass density ($\Sigma_*$), SFR density ($\Sigma_{\text{SFR}}$), and specific SFR (sSFR) derived from the single-stellar population (SSP) analysis. The $\Sigma_{\text{SFR}}$ is obtained as the ratio between the mass of stars formed in the last temporal bin (0.06 Gyr) and the total mass of stars formed across cosmic time. From the emission line analysis, we obtain for each spaxel the extinction-corrected $\Sigma_{\text{SFR}}$ derived from the H alpha emission line luminosity ($\Sigma_{\text{SFR}}(H\alpha)$) and equivalent width (EW(Halpha)). In Barrera-Ballesteros et al. (2020), we derived a linear correlation between $\Sigma_{\text{gas}}$ ($\Sigma_{\text{gas}} = \Sigma_{\text{mol}} + \Sigma_{H_2}$) and the optical extinction ($A_V$). The $A_V$ was derived from the Balmer decrement, whereas $\Sigma_{H_2}$ was derived from CO-resolved maps observed within the EDGE survey (Bolatto et al. 2017). We found that $\Sigma_{\text{gas}} (M_\odot$ pc$^{-2}$) $\sim 26 A_V$ (mag) for radial scales. With the same data set, we derived in J. K. Barrera-Ballesteros et al. (2021, in preparation) a linear log–log calibrator for the molecular gas mass density with $\Sigma_{H_2}$/Av = $10^{3.7}[A_V(\text{mag})]^{2.3}$ using a least trimmed square fitting at kiloparsec scales (Cappellari et al. 2013). In comparison to the linear calibrator, it improves the estimation of $\Sigma_{\text{mol}}$ for high values of $A_V$. Furthermore, we found that this calibration depends on the inclination; therefore, we use it only for low-inclined galaxies. All of the intensive observables are corrected by inclination following Barrera-Ballesteros et al. (2016).

For this study, we select those regions (spaxels) that we consider bona fide star-forming in low-inclined galaxies ($b/a > 0.45$)\(^{12}\). A spaxel is considered star-forming if (i) the [N II]/H$\alpha$ and [O III]/H$\beta$ emission line flux ratios are below the Kewley et al. (2001) demarcation line in a BPT diagram (Baldwin et al. 1981), (ii) the H$\alpha$ and H$\beta$ emission lines have a signal-to-noise ratio larger than 3, (iii) H$\alpha$/H$\beta > 2.86$, and (iv) EW(H$\alpha$) > 14 Å. These criteria lead to selecting more than $1.1 \times 10^6$ star-forming spaxels located in 2640 galaxies included in the MaNGA sample. We should note that due to the spatial resolution of this survey ($\sim 2''$), the number of spaxels overestimates the number of independent H II regions detected in the survey by at least a factor of $\sim 5$.

#### 3.2. Single-variable Scaling Relation: rSK and rSFMS

In Figure 1, we show the rSK and rSFMS derived for our sample of galaxies (left and right panels, respectively). The observables for this study are determined by applying the PIPE3D analysis pipeline to the MaNGA data cubes. A full description of this pipeline and its stellar and emission line fitting, uncertainty estimations, and derivation of physical properties can be found in Sánchez et al. (2016). An overview of how the two-dimensional distributions of stellar and gas components are derived for MaNGA data can be found in Barrera-Ballesteros et al. (2016, 2018). In particular, for this study, we use the stellar surface mass density ($\Sigma_*$), SFR density ($\Sigma_{\text{SFR}}$), and specific SFR (sSFR) derived from the single-stellar population (SSP) analysis. The $\Sigma_{\text{SFR}}$ is obtained as the ratio between the mass of stars formed in the last temporal bin (0.06 Gyr) and the total mass of stars formed across cosmic time. From the emission line analysis, we obtain for each spaxel the extinction-corrected $\Sigma_{\text{SFR}}$ derived from the H alpha emission line luminosity ($\Sigma_{\text{SFR}}(H\alpha)$) and equivalent width (EW(Halpha)). In Barrera-Ballesteros et al. (2020), we derived a linear correlation between $\Sigma_{\text{gas}}$ ($\Sigma_{\text{gas}} = \Sigma_{\text{mol}} + \Sigma_{H_2}$) and the optical extinction ($A_V$). The $A_V$ was derived from the Balmer decrement, whereas $\Sigma_{H_2}$ was derived from CO-resolved maps observed within the EDGE survey (Bolatto et al. 2017). We found that $\Sigma_{\text{gas}} (M_\odot$ pc$^{-2}$) $\sim 26 A_V$ (mag) for radial scales. With the same data set, we derived in J. K. Barrera-Ballesteros et al. (2021, in preparation) a linear log–log calibrator for the molecular gas mass density with $\Sigma_{H_2}$/Av = $10^{3.7}[A_V(\text{mag})]^{2.3}$ using a least trimmed square fitting at kiloparsec scales (Cappellari et al. 2013). In comparison to the linear calibrator, it improves the estimation of $\Sigma_{\text{mol}}$ for high values of $A_V$. Furthermore, we found that this calibration depends on the inclination; therefore, we use it only for low-inclined galaxies. All of the intensive observables are corrected by inclination following Barrera-Ballesteros et al. (2016).

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outermost black contour encloses 95% of the distributions. The solid circles represent the median \( \Sigma_{\text{SFR}} \) for bins of equal width (0.2 dex) on \( \Sigma_{\text{mol,Av}} \) and \( \Sigma_\ast \). The black solid lines represent a least-squares linear fit of those median values in log scales. We use the relation \( \log(\Sigma_{\text{SFR}}) = a + b \log(\Sigma) \), where \( \Sigma \) represents both \( \Sigma_{\text{mol}} \) and \( \Sigma_\ast \). Following Cano-Díaz et al. (2019), in order to perform the above fit for both relations, we use those bins where we consider that we have reliable estimations of \( \Sigma_{\text{mol,Av}} \) and \( \Sigma_\ast \). For the rSK relation, we select those bins with \( \Sigma_{\text{mol,Av}} > 10^{7.0} \, M_\odot \, \text{kpc}^{-2} \). This limit is motivated by the gas calibrator used in this study. In J. K. Barrera-Ballesteros et al. (2021, in preparation), we show that due to the sensitivity of the CO observations (from the EDGE survey; Bolatto et al. 2017), the calibrator may not be reliable at a \( \Sigma_{\text{mol,Av}} \) smaller than this limit. On the other hand, to perform the fitting in the rSFMS, Cano-Díaz et al. (2019) used bins with \( \Sigma_\ast > 10^{7.5} \, M_\odot \, \text{kpc}^{-2} \). They noted a nonphysical driven flattening of the rSFMS below the mentioned \( \Sigma_\ast \) due to detection limits in each of the observables. Both of these limits are represented as vertical dashed lines in Figure 1. In both panels, the horizontal dashed line represents the \( \text{H} \alpha \) surface brightness detection limit for the MaNGA survey (\( \sim 10^{−17} \, \text{erg} \, \text{s}^{-1} \, \text{kpc}^{-2} \); Cano-Díaz et al. 2019).

Both scaling relations present significant Pearson correlation coefficients \( (r) \). In fact, our rSFMS shows a higher \( r \) coefficient in comparison to previous studies using MaNGA data (e.g., Cano-Díaz et al. 2019; Lin et al. 2019). However, the \( r \) coefficient for the rSK relation is smaller in comparison to the value derived for the rSFMS relation (0.48 versus 0.72). This could be caused by the larger scatter observed in the rSK compared to the rSFMS. We also note that in comparison to other relations presented in the literature, our rSK shows a smaller correlation factor (e.g., Lin et al. 2019). We compare the best fit for each relation with those that illustrate the trends observed from the EDGE survey (Bolatto et al. 2017), which makes use of CO maps to estimate \( \Sigma_{\text{gas}} \) in a sample of 123 galaxies. The best fit for the rSK derived using the MaNGA data is flatter in comparison to the relation derived by Bolatto et al. (2017). We suggest that this flattening is due to the nature of our data set. For low values of \( \Sigma_{\text{SFR}} \), we could be sampling physical regions for which \( \text{H} \alpha \) flux emission could be potentially polluted from processes other than young stellar emission (e.g., diffuse \( \text{H} \alpha \) emission from old stars; Lacerda et al. 2018). In turn, this causes an underestimation of \( \Sigma_{\text{gas}} \) from the calibrator. By diluting HII regions along with diffuse \( \text{H} \alpha \) emission, the spatial resolution can also have an impact on the scatter of the rSK (e.g., Vale Asari et al. 2020). However, for large values of \( \Sigma_{\text{SFR}}, \, \Sigma_{\ast} \) the amount of dust traces \( \Sigma_{\text{mol}} \). Indeed, when selecting spaxels with EW(\( \text{H} \alpha \)) larger than 30 \( \text{Å} \), the best linear fit is steeper than the one derived from the median values (green dashed line) and close to the linear relation reported using direct CO measurements by the EDGE survey (Bolatto et al. 2017). On the other hand, the rSFMS is in very good agreement with those derived previously using the EDGE and MaNGA data sets (Bolatto et al. 2017; Cano-Díaz et al. 2019).

In both panels, we also annotate the scatter of the residuals, \( \sigma \). We use two measurements, the standard deviation and the variance. By comparing \( \sigma \) between these two relations, we note that the rSK shows a larger scatter in comparison to the rSFMS (\([0.45, 0.20]\) versus \([0.31, 0.10]\)).

The scatter of the rSK is only \( \sim 0.01 \) dex larger in comparison to the rSK relation derived using direct observations of molecular gas in a smaller sample of MaNGA galaxies (Lin et al. 2019). In other words, the scatter of the relation remains similar as more galaxies are probed. On the other hand, it may be the case that the gas estimator could artificially increase the scatter. However, it would be very difficult to provide direct spatially resolved observations of the gas density for the sample of galaxies presented in this study. So far, the largest overlap of IFS data with spatially resolved CO observations comprises only 126 galaxies from the EDGE-CALIFA survey (Bolatto et al. 2017). Other similar efforts, like the ALMAQUEST compilation, comprise 47 MaNGA galaxies extracted from different scientific projects (Lin et al. 2019).

We also note that the scatter of the rSFMS is reduced in comparison to other estimations of the rSFMS using the MaNGA data set (e.g., Hsieh et al. 2017; Cano-Díaz et al. 2019; Lin et al. 2019). This suggests that using a larger sample...
of galaxies can only mildly reduce the statistical scatter of this relation.

3.3. The Linear $\Sigma_{\text{SFR}}-\Sigma_b$ Relation

One of the goals of this study is to probe what is the best relation of the baryonic mass ($\Sigma_h = \Sigma_{\text{mol,Av}} + \Sigma_*$) with respect to the $\Sigma_{\text{SFR}}$. First, we show the direct relation between these two parameters in Figure 2. To our knowledge, this is the first time that this scaling relation has been explored for such a large sample of galaxies at kiloparsec scales. The distribution of this relation is drawn from the same regions used in the relations explored in Figure 1. We note that the distribution of spaxels in the $\Sigma_{\text{SFR}}-\Sigma_b$ plane does not show the strong flattening observed at low values of $\Sigma_b$ in the rSK and rSFMS relations (see Figure 1).

The distribution seems to follow a tighter relation than the single-parameter local star-forming relations explored in Figure 1 (i.e., lower scatter). In fact, the $r$ coefficient indicates a stronger correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_b$ than the relations derived in Section 3.2. For instance, the $r$ coefficient is larger for this relation than for the rSFMS $(0.77$ versus $0.72)$. We follow a similar procedure to derive the best-fit relation as in Section 3.2. We choose a $\Sigma_b$ threshold to select the bins to perform the fit ($\Sigma_b \geq 10^{9.6} M_\odot$ kpc$^{-2}$; this is the sum of the thresholds in Section 3.2). However, we should note that the results are not strongly affected by the implementation of this limit in the analysis. The best-fit parameters (slope and zeropoint) are shown in Figure 2. Both parameters of the best fit are similar to those derived from the rSFMS (see Figure 1). This is expected, since the main driver in the baryonic mass density is $\Sigma_*$.

Nevertheless, it is important to note the role of $\Sigma_{\text{gas}}$ in shaping the $\Sigma_{\text{SFR}}-\Sigma_b$ relation at low values of $\Sigma_b$, as well as increasing the slope of the best relation, making it close to 1. This can also be noted in the decrease in the scatter of the $\Sigma_b-\Sigma_{\text{SFR}}$ relation in comparison to the rSFMS. Finally, the scatter of the residuals with respect to this fit is smaller than the rSFMS ($\sigma = [0.28, 0.08]$ versus $\sigma = [0.31, 0.10]$), indicating a tighter relation than the ones derived by individual components of $\Sigma_b$.

3.4. Impact of a Quadratic Term in the $\Sigma_b-\Sigma_{\text{SFR}}$ Relation

As we mentioned in Section 1, there are different studies exploring scaling relations between the star formation and the $\Sigma_{\text{gas}}$ - $\Sigma_*$ product or similar relations. These relations have been studied in order to explore the self-regulated star formation scenario. In this section, we explore a rather generic approach. We investigate the relation of $\Sigma_{\text{SFR}}$ with a second-degree polynomial of $\Sigma_b$. Using this functional form, we explore both the dependence of $\Sigma_{\text{SFR}}$ with respect to mixed quadratic terms ($\Sigma_{\text{gas}}$-$\Sigma_*$) and the quadratic terms of $\Sigma_{\text{gas}}$-$\Sigma_*$.

In Figure 3, we plot the relation between $x_{\text{new}} = a \Sigma_b + b \Sigma_*$ and $\Sigma_{\text{SFR}}$. The fit between $x_{\text{new}}$ and $\Sigma_{\text{SFR}}$ is obtained by using the median values of $\Sigma_b$ and $\Sigma_{\text{SFR}}$ derived in Figure 2. This fit yields the values of $\log(a) = -10.21$ and $\log(b) = -20.37$. The spaxels in the $\Sigma_{\text{SFR}}-x_{\text{new}}$ plane lie in a well-defined linear trend. In fact, the best linear fit derived from the median $\Sigma_{\text{SFR}}$ for different $x_{\text{new}}$ bins yields a one-to-one relation (black solid line in Figure 3). In contrast to the single-variable scaling relations (rSK and rSFMS; see Section 3.2), the above relation does not show strong deviations or flattening at low values of $x_{\text{new}}$. We perform the same analysis using each of the components of $\Sigma_b$ separately. We find that by fitting a quadratic polynomial using $\Sigma_*$ or $\Sigma_{\text{mol,Av}}$ as independent variables, there is no significant reduction in the scatter, and it is not possible to obtain a one-to-one relation from the medians, as we find using $\Sigma_b$. Therefore, our results indicate that a better representation between $\Sigma_{\text{SFR}}$ and the baryonic mass is given by a second-degree polynomial rather than considering each of its components separately.

The best-fit relation between $\Sigma_{\text{SFR}}-x_{\text{new}}$ yields a similar scatter and a larger $r$-correlation factor compared to those derived with $\Sigma_b$ alone. To test how this relation can be affected by the number of sampled galaxies, we derive the same figures in this analysis using the data set from the previous internal release (MPL8; ~6400 galaxies). We find the same results in terms of slopes and scatters as those drawn from the current sample. These results may suggest that the residuals observed in the $\Sigma_{\text{SFR}}-\Sigma_b$ relation, as well as the $\Sigma_{\text{SFR}}-x_{\text{new}}$ relation, may...
be due to the statistical distribution of the observables. We note that despite the linear slope derived including a quadratic term, the best-fit coefficients are small; in particular, the factor that multiplies the quadratic term of \( \Sigma \) is several orders of magnitude smaller than the factor that accompanies the linear term of \( \Sigma \). The derivation of a slope of 1 is expected because, as we mention in Section 3.3, the stellar mass density is the dominant term in \( \Sigma \), in particular for regions with large SFRs.

3.5. An Independent Measure of \( \Sigma_{\text{SFR}} \) via SSPs

In the previous sections, we derive the scaling relations between the \( \Sigma_{\text{SFR}} \) and the different functions of the baryonic mass using the H\( \alpha \) luminosity as the observable to derive \( \Sigma_{\text{SFR}} \). Similarly, we estimate \( \Sigma_{\text{gas}} \) from the H\( \alpha \)/H\( \beta \) emission line ratio (Balmer decrement). Therefore, it can be the case that, since we are using similar observables to determine the above scaling relations, we could be inducing such relations. In order to test this, we use in this section another estimation of \( \Sigma_{\text{SFR}} \). As we mention in Section 3.1, the PIIPE3D data analysis pipeline allows us, through the fitting of SSPs to the stellar continuum of each spaxel, to determine the average star formation at different cosmic times (their SFHs; Ibarra-Medel et al. 2019), among other properties of the stellar component. For the purposes of this study, we understand \( \Sigma_{\text{SFR,SSP}} \) as the fraction of the latest stellar burst measured by the SSP fitting (i.e., the fraction of stars formed in a span of time smaller than \( \sim 32 \) Myr; González Delgado et al. 2016). Besides the selection criteria described in Section 3.1, for this section, we only consider spaxels with an sSFR(SSP) > 10\(^{-10}\) yr\(^{-1}\). As result, the sample for this experiment consists of 3.1 \times 10\(^3\) spaxels located in 2098 galaxies. In the Appendix, we compare the estimation of \( \Sigma_{\text{SFR}} \) using SSPs (\( \Sigma_{\text{SFR,SSP}} \)) with the one derived using H\( \alpha \) luminosity (\( \Sigma_{\text{SFR,H}\alpha} \)). We note that they strongly correlate with each other (\( r = 0.73 \)). In particular, they are similar at large values. On average, \( \Sigma_{\text{SFR,SSP}} \) is overestimated by a factor of 1.3 in comparison to \( \Sigma_{\text{SFR,H}\alpha} \). Different studies showed that scaling relations at global and local scales derived using either \( \Sigma_{\text{SFR,SSP}} \) or \( \Sigma_{\text{SFR,H}\alpha} \) are similar (e.g., the rSFMS; see González Delgado et al. 2014, 2016; Sánchez et al. 2018).

In Figure 4, we plot the same relations from Figures 2 and 3 using \( \Sigma_{\text{SFR,SSP}} \). We find similar results when we derive the \( \Sigma_{\text{SFR}} \) relation using \( \Sigma_{\text{SFR,SSP}} \) instead of \( \Sigma_{\text{SFR,H}\alpha} \). However, the distribution is above the relation derived using \( \Sigma_{\text{SFR,H}\alpha} \) (see dashed line). Although the trend is similar, the slope of this relation is shallower than the one derived using the H\( \alpha \) proxy for \( \Sigma_{\text{SFR}} \); it also presents a scatter larger than the one derived in Section 3.3. In right panel of Figure 4, we plot the \( \Sigma_{\text{SFR,x_{new}} \) relation following the same procedure as in Section 3.4. We note that the coefficients of the fit for \( x_{new} \) are different from those derived in Section 3.4 (\( a = 2.3 \times 10^{-10} \) and \( b = -9.6 \times 10^{-20} \)). Nevertheless, the distribution of this relation is similar to the one derived using \( \Sigma_{\text{SFR,H}\alpha} \) with a smaller correlation coefficient than the relation derived in Section 3.4. The median values of \( \Sigma_{\text{SFR,SSP}} \) for different bins of \( x_{new} \) are in good agreement with respect to the best relation derived in Section 3.4 (see dashed line) despite the increment in the scatter observed for this relation (\( \sigma = 0.39, 0.15 \)). Furthermore, the best fit of these medians is in agreement with the dashed line.

Finally, we plot the \( \Sigma_{\text{SFR}, x_{new} \) relation following the same procedure as in Section 3.4 (see right panel of Figure 4). We note that the coefficients of the fit for \( x_{new} \) are different from the ones derived in Section 3.4 (\( a = 2.3 \times 10^{-10} \) and \( b = -9.6 \times 10^{-20} \)). Nevertheless, the distribution of this relation is similar to the one derived using \( \Sigma_{\text{SFR,H}\alpha} \) with a smaller correlation coefficient than the relation derived in Section 3.4. The median values of \( \Sigma_{\text{SFR,SSP}} \) for different bins of \( x_{new} \) are in good agreement with respect to the best relation derived in Section 3.4 (see dashed line) despite the increment in the scatter observed for this relation (\( \sigma = 0.39, 0.15 \)). Furthermore, the best fit of the median values derived using \( \Sigma_{\text{SFR,SSP}} \) is similar to the one reported using \( \Sigma_{\text{SFR,H}\alpha} \).

In summary, these results suggest that, independent of the observable we use to determine \( \Sigma_{\text{SFR}} \), we obtain similar trends when we derive the \( \Sigma_{\text{SFR}} \)–\( b \) relation. Also, the inclusion of an extra quadratic term to describe this relation leads to similar results regardless of the \( \Sigma_{\text{SFR}} \) calibrator.

4. Discussion

In this paper, we present the well-known star-forming scaling relations between each of the components of the baryonic mass at kiloparsec scales (i.e., the rSK and rSFMS) for the largest IFU data set provided by the MaNGA survey (\( \sim 8000 \) galaxies). The gas mass density is derived using the
optical extinction obtained from the Balmer decrement following J. K. Barrera-Ballesteros et al. (2021, in preparation). We further explore different scaling relations between star formation and the baryonic mass, including a quadratic polynomial of the baryonic mass. We also test these scaling relations using an independent measurement of the $\Sigma_{\text{SFR}}$ derived from the SSP analysis.

The main result of this work is that $\Sigma_b$ provides a better correlation with $\Sigma_{\text{SFR}}$ than using only each of its two components ($\Sigma_*$ and $\Sigma_{\text{mol, Av}}$). Furthermore, when adopting a quadratic polynomial form of $\Sigma_b$, the log–log relation presents a one-to-one slope (i.e., no power is required to match both quantities). We find similar results when using an independent observable to estimate the SFR density. This analysis highlights the necessity of considering the full baryonic content, not just the separate terms of $\Sigma_b$, to properly describe the star formation at kiloparsec scales. Such a nonlinear empirical relation has been pointed out as evidence of the importance of the impact of existing stars in the regulation of SFR (e.g., Zaragoza-Cardiel et al. 2019). In this self-regulated model of star formation, the hydrostatic pressure of the disk galaxy is balanced by the momentum flux injected into the interstellar medium from supernova explosions (e.g., Cox 1981; Silk 1997; Ostriker et al. 2010). From our main result, we argue that a second-degree polynomial of $\Sigma_b$ provides a better description of $\Sigma_{\text{SFR}}$, since it includes both the contribution of the amount of gas required to form new stars and the nonlinear terms that describe the impact of the hydrostatic pressure of the disk (see Section 4.1).

In this paper, we measure the scatter of the different scaling relations derived for star formation regions at kiloparsec scales. For individual components of the baryonic mass, we find that the rSFMS yields the smallest scatter, in agreement with the scatter derived for a smaller sample of the same MaNGA galaxies (standard deviation $\sim 0.27$ dex; Cano-Díaz et al. 2019). On the other hand, the relation derived with $\Sigma_b$ has a slightly smaller scatter with stronger correlation coefficients. These results indicate that when using this specific combination of the baryonic components, the main driver to derive $\Sigma_{\text{SFR}}$ in star-forming regions is the stellar mass density. This has also been found in recent studies that classify the strength of the correlations among star formation and other observables at kiloparsec scales. Their results suggest that $\Sigma_b$ appears to be the observable that better correlates with $\Sigma_{\text{SFR}}$ (Dey et al. 2019; Bluck et al. 2020). On the contrary, other explorations, using estimations of the molecular gas based on CO observations of a few tens of objects, suggest that the strongest and tightest correlation is found with $\Sigma_{\text{mol}}$ (Lin et al. 2019; Ellison et al. 2020).

Overall, molecular gas is essential to form new stars at kiloparsec scales; however, the regulation of $\Sigma_{\text{SFR}}$ strongly depends on the amount of baryonic matter. In other words, we suggest that locally, the gravitational potential is the main regulator of the SFR. In Barrera-Ballesteros et al. (2021), we explore the explicit relation between star formation and the midplane pressure derived from direct estimation of the molecular gas, as well as its interpretation in the context of self-regulation.

4.1. Other Nonlinear Relations: Revisiting the Extended Schmidt Law

As indicated before, in recent years, there have been different studies exploring the relation of a combination of the components of the baryonic mass with star formation (e.g., Westfall et al. 2014; Bolatto et al. 2017; Dib et al. 2017; Roychowdhury et al. 2017; de los Reyes & Kennicutt 2019; Sun et al. 2020). In particular, Shi et al. (2011, 2018) explored the so-called extended Schmidt law, which correlates the star formation surface density with the product of the stellar and gas mass surface density. Shi et al. (2011) suggested that $\Sigma_{\text{SFR}} \sim \Sigma_\ast \times \Sigma_{\text{gas}}$ provides a better relation than the Schmidt law. In other words, the scatter of this extended Schmidt law is reduced in comparison to the $\Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}$ relation. Furthermore, in Shi et al. (2018), they showed that the best relation is slightly superlinear ($\Sigma_{\text{SFR}} = 10^{-4.76} \Sigma_\ast^{0.5} \Sigma_{\text{gas}}^{1.09}$). In Figure 5, we explore this extended star formation law using the current MaNGA data. The slope of the best fit of the median values ($\sim 0.67$; black solid line) is smaller than the one reported by Shi et al. (2018; red dashed line). The slope derived by Shi et al. (2018) is similar to the one presented by Bolatto et al. (2017) using the EDGE-CALIFA data set (blue dashed line). Similarly to the rSK and rSFMS relations (see Figure 1), to perform the best fit, we use the median values of $\Sigma_{\text{SFR}}$ larger than a threshold in the x-axis ($10^{1.79} (M_\odot \text{ pc}^{-2})^{1.3}$; gray dashed vertical line). This threshold considers the limits we use for $\Sigma_{\text{mol, Av}}$ and $\Sigma_\ast$. The scatter of this relation is smaller than the one we derive for the rSK (standard deviation of 0.36 and 0.45 dex, respectively). However, this scatter has a larger dispersion in comparison to the one derived from the rSFMS (0.31 dex). Furthermore, its correlation coefficient is significantly smaller than the one derived for the rSFMS ($r = 0.41$ versus 0.72). We also note that even though the slope from the best fit is sublinear, the $\Sigma_{\text{SFR}}$ derived for large values of $\Sigma_{\text{gas}}$, $\Sigma_\ast$, is in agreement with the relations derived in the literature, suggesting that for regions with intense star formation, $\Sigma_{\text{gas}}$ and $\Sigma_\ast$ play an important role in describing $\Sigma_{\text{SFR}}$. In further studies, we explore the explicit relation between $\Sigma_{\text{SFR}}$ and baryonic mass in the context of the self-regulation of star formation in order to quantify the role of the midplane pressure in shaping the SFR at kiloparsec scales (Barrera-Ballesteros et al. 2021).

Recently, Lin et al. (2019) explored the functional form of the extended SK law ($\Sigma_{\text{gas}} \sim \Sigma_\ast^{3} \Sigma_b^{-2}$). Using a homogeneous data set, they found that the exponential that yields the smallest scatter in this relation is $\beta \sim -0.30$. Even when using this exponential, the scatter in comparison to the rSK or rSFMS is not reduced, as expected from Shi et al. (2011, 2018). Like these authors, we do not find a strong reduction of the scatter for the star formation when using the functional form described by Shi et al. (2018). From our analysis, we conclude that although a relation such as the extended Schmidt law—which is derived in the context of self-regulation of star formation—is necessary to describe the $\Sigma_{\text{SFR}}$, it may also need to include other contributions of the baryonic mass, such as the second-degree polynomial relation presented in Section 3.4.

5. Summary and Conclusions

Using a sample of more than $1.1 \times 10^6$ spatial elements ($\sim 3 \times 10^5$ independent regions) of kiloparsec size located in 2640 galaxies drawn from the MaNGA survey—the largest IFU survey to date—we present a scaling relation between the SFR surface density ($\Sigma_{\text{SFR}}$) and the baryonic mass surface density ($\Sigma_b = \Sigma_{\text{gas}} + \Sigma_\ast$). Here $\Sigma_{\text{gas}}$ is obtained by using the optical extinction as a proxy. Our results can be summarized as follows.
Figure 5. Extended star-forming law at kiloparsec scales for the MaNGA sample. The x-axis is defined by Shi et al. (2011). The distribution of the selected spaxels (i.e., values larger than the gray dashed vertical line) and their median values of $\Sigma_{\text{SFR}}$ (white circles) follows a similar relation as the one derived by Shi et al. (2018; red dashed line). Although our sample follows the trend of the proposed extended scaling relation by Shi et al. (2018), its scatter is similar to the one derived for the rSFMS (see right panel of Figure 1).

1. We reproduce the well-known star-forming scaling relations for the individual components of $\Sigma_b$: the rSK and rSFRMS. By measuring their scatter and correlation factors, we find that the rSFRMS yields the tighter and stronger relation with respect to $\Sigma_{\text{SFR}}$.

2. We derive a scaling relation between $\Sigma_{\text{SFR}}$, $\Sigma_b$, and a second-degree polynomial of $\Sigma_b$. These relations show a strong correlation and a smaller scatter than those derived from individual components of $\Sigma_b$. In particular, the second one naturally yields a one-to-one relation. We find similar trends using two independent indicators of $\Sigma_{\text{SFR}}$: the Hα emission line luminosity and a stellar decomposition using SSP fitting of the stellar continuum.

3. We contrast these new relations with other empirical star-forming scaling relations, such as the extended Schmidt law proposed by Shi et al. (2011, 2018). We find that the $\Sigma_{\text{SFR}}$-$\Sigma_b$ relation yields a stronger correlation and has a smaller scatter in comparison to the extended Schmidt law.

We conclude that these star-forming scaling relations quantify the strong impact of the baryonic mass as a whole in the conditions of formation of newly born stars at kiloparsec scales. Furthermore, besides the evident role that $\Sigma_{\text{gas}}$ has in the formation of stars, these relations suggest that the local gravitational potential—measured from the total baryonic mass density—plays a significant role in shaping the SFR. These results also favor the scenario where star formation is self-regulated at kiloparsec scales. In future work, we will explicit study the relation between the hydrostatic pressure of the disk and the SFR density at kiloparsec scales.

Appendix

$\Sigma_{\text{SFR}}$ Estimations

In Section 3.5, we use the $\Sigma_{\text{SFR}}$ derived from the SSP to estimate the star-forming scaling relations derived using the Hα luminosity as a proxy of $\Sigma_{\text{SFR}}$. In this Appendix, we compare these two independent estimations of this quantity. In Figure 6, we compare the $\Sigma_{\text{SFR}}$ derived using SSPs against the one derived using Hα luminosity for the sample of spaxels selected in Section 3.5.
circles show the median plots, the contours enclose 90%, 80%, and 60% of the distribution. The white estimations of $\Sigma_{Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5}$

Figure 6. A comparison between the star formation derived from the SSP analysis, $\Sigma_{SFR,SSP}$, against the one derived using the H$\alpha$, luminosity $\Sigma_{SFR,H\alpha}$. As in previous plots, the contours enclose 90%, 80%, and 60% of the distribution. The white circles show the median $\Sigma_{SFR,SSP}$, for bins of $\Sigma_{SFR,H\alpha}$. The solid lines show the best fit of these bins whereas the dashed lines represent the one-to-one relation. Both estimations of $\Sigma_{SFR}$ are similar to each other.

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