A quantitative demonstration that stellar feedback locally regulates galaxy growth

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We have applied stellar population synthesis to 500 pc sized regions in a sample of 102 galaxy discs observed with the MUSE spectrograph. We derived the star formation history and analyse specifically the “recent" (20Myr) and “past” (570Myr) age bins. Using a star formation self-regulator model we can derive local mass-loading factors, \( \eta \), for specific regions, and find that this factor depends on the local stellar mass surface density, \( \Sigma^* \), in agreement with the predictions from hydrodynamical simulations including supernova feedback. We integrate the local \( \eta \Sigma^* \) relation using the stellar mass surface density profiles from the Spitzer Survey of Stellar Structure in Galaxies (S4G) to derive global mass-loading factors, \( \eta_G \), as a function of stellar mass, \( M^* \). The \( \eta_G-M^* \) relation found is in very good agreement with hydrodynamical cosmological zoom-in galaxy simulations. The method developed here offers a powerful way of testing different implementations of stellar feedback, to check on how realistic are their predictions.

Key words: galaxies: evolution – galaxies: formation – galaxies: star formation – galaxies: stellar content

1 INTRODUCTION

Understanding the global star formation process in galaxies is of key importance in the comprehension of galaxy formation and evolution. One of the biggest challenges faced by numerical models of galaxy formation derived directly from cosmological models is to explain why the stellar masses of galaxies are consistently lower than those expected from the simulations (Silk & Mamon 2012). This difference has been bridged by invoking internal mechanisms capable of regulating the star formation rate. Two regimes have been generally used: for massive galaxies their nuclear activity is found to be a mechanism which acts in this way (Martín-Navarro et al. 2018). But for low mass galaxies the star formation itself, through feedback, appears to offer a satisfactory mechanism to reduce the star formation rate, making star formation an inefficient process when comparing the stars which are formed with the availability of gas to form them (Bigiel et al. 2008; Hopkins et al. 2014; Kruijssen et al. 2019). Star formation self-regulates by expelling gas, and the amount of gas that flows out of any system is considered to depend on the mass of stars formed.

The models used to explain the consistently low mean star formation rate (SFR) efficiency use sub-grid physics parametrised by a mass loading factor, \( \eta \), relating the mass outflow rate \( M_{\text{out}} \) and the SFR by \( M_{\text{out}} = \eta \text{SFR} \) (Schaye et al. 2010; Vogelsberger et al. 2013; Somerville & Davé 2015; Hopkins et al. 2018).

This factor can be predicted by modelling the feedback process (Creasey et al. 2013; Muratov et al. 2015; Li et al. 2017), or inferred from observations (Schroetter et al. 2019; McQuinn et al. 2019; Kruijssen et al. 2019; Roberts-Borsani et al. 2020). However feedback modelling has many uncertainties, and the required observations are scarce and also subject to uncertainty. The present article marks a significant step in making up for the observational deficiencies.
In order to see whether the star formation at different epochs is correlated and to quantify it by estimating the mass-loading factor we apply an empirical method based on stellar population synthesis and the self-regulator model of star formation, which has been presented previously (Zaragoza-Cardiel et al. 2019).

The star formation self-regulator model (Bouché et al. 2010; Lilly et al. 2013; Dekel & Mandelker 2014; Forbes et al. 2014; Ascasibar et al. 2015) assumes mass conservation for a galaxy, which implies that the change per unit time of the gas mass, $M_{\text{gas}}$, equals the inflow rate into the galaxy, $M_{\text{in}}$, minus the gas that goes into star formation, SFR, and the gas which flows out of the galaxy, $M_{\text{out}}$:

$$M_{\text{gas}} = M_{\text{in}} - \text{SFR}(1 - R + \eta). \quad (1)$$

where $R$ is the fraction of the mass which is returned to the interstellar medium from the stellar population.

The spatially resolved star formation self-regulator model applies to segments of a galaxy (Zaragoza-Cardiel et al. 2019), where by segment we mean any spatially resolved region of a galaxy. In these resolved regions we also assume conservation of mass: the time change of the gas mass surface density in a segment, $\Sigma_{\text{gas}}$, is equal to the surface density of the net gas flow rate, $\Sigma_{\text{net flow}}$, minus the surface density of the gas that goes into new stars through star formation, $\Sigma_{\text{SFR}}$, and minus the surface density of gas that is expelled from the segment by stellar processes, $\Sigma_{\text{out}}$:

$$\Sigma_{\text{gas}} = \Sigma_{\text{net flow}} - \Sigma_{\text{SFR}}(1 - R + \eta) \quad (2)$$

where $R$ is the fraction of the mass that is returned to the interstellar medium, and

$$\Sigma_{\text{out}} = \eta \Sigma_{\text{SFR}}. \quad (3)$$

This model allows us to relate the star formation rate surface density in a segment, $\Sigma_{\text{SFR}}$, to the change in gas mass in that segment. The complex processes of stellar feedback are parameterized by the mass-loading factor: $\Sigma_{\text{out}} = \eta \Sigma_{\text{SFR}}$.

We present the galaxy sample and the data in section §2. In section §3 we give the stellar population synthesis fits and also fit the observables to the star formation self-regulator model. In section §4 we show the results obtained, and the variation of $\eta$, while in section §5 we convert local values of $\eta$ into global ones. We discuss our results in section §6 and present our conclusions in section §7.

## 2 GALAXY SAMPLE AND DATA

### 2.1 Galaxy sample

A significant number of galaxies have been observed with the MUSE instrument on the VLT in different surveys (Poggianti et al. 2017; Sánchez-Menguiano et al. 2018; Kreckel et al. 2019; Erroz-Ferrer et al. 2019; López-Cobá et al. 2020).

To use these observations we build our sample using the Hyperleda database and looking for them in the MUSE archive. To be able to apply the method for a given galaxy, we need to resolve the galaxy at a specific spatial scale. Based on results of NGC 628 (Zaragoza-Cardiel et al. 2019), we choose the 500pc scale to study the star formation self-regulation so we are limited to galaxies closer than 100Mpc to resolve 500pc at 1arsec resolution. We also need enough (~16) resolution elements, so very nearby galaxies with low number of 500pc resolution elements are not useful. We will divide the MUSE field of view in squares, so we will need at least 4$x$4 500pc squares per galaxy, limiting us to galaxies further away than 7Mpc.

We need galaxies with recent star formation to study star formation self-regulation. To ensure that we will detect recent star formation, we just consider Sa or later types morphology (Hubble type $T \geq 1.0$ in Hyperleda). We discard edge-on galaxies ($i = 90$deg), galaxies classified as multiple, Irregulars (Hubble type $T \geq 9$ in Hyperleda), and LIRGs (in NASA NED). We just select galaxies with declination lower than 45degN to be observable from Paranal Observatory.

The SQL (Structured Query Language) search through Hyperleda selects 13636 galaxies, of which 164 have been observed with MUSE on the VLT and have publicly available data with an exposure time at least of 1600 seconds. We also removed galaxies in Arp (Arp 1966), Vorontsov-Velyaminov (Vorontsov-Velyaminov 1959), and Hickson Compact Group (Hickson 1982) catalogs, to get rid out of strong external effects on the star formation history (SFH) and gas flows due to interactions. We have a total of 148 galaxies satisfying these conditions in the public MUSE archive. Of these, 9 galaxies did not pass our requirements in a spectral inspection by eye, because of clear spectral artifacts, or not having enough H$\alpha$ emission in the pointing (MUSE has a square 1arcmin $\times$ 1arcmin FOV). We initially analysed the single stellar populations (SSP’s) of the remaining 139 galaxies, to apply the method described in this article. Since the method requires enough regions to be included in the analysis, we set this limit to 16 (4$x$4). However each of the 16 regions sampled per galaxy needs sufficient current SFR, sufficient signal to noise, and that can be properly reproduced with stellar population synthesis models. Finally, only 102 galaxies satisfied all the conditions allowing us to estimate $\eta$. We present their parameters in Table 1.

### 2.2 MUSE spectral data

We use the MUSE (Bacon et al. 2010) reduced publicly available data for the galaxies listed in Table 1, from the ESO archive.

We first made a visual inspection to remove galaxies with no H$\alpha$ emission in the MUSE pointing, and thus to select MUSE fields where H$\alpha$ was observed, to be able to estimate recent star formation. After delimiting the regions with recent star formation, we divide each field into an integer number of observing squares, giving us squares with the closest (and larger than) size value to 500 pc. We show an example in Fig. 1. We do not use the squares outside the MUSE pointing. We choose 500 pc because it gives us a scale on which, from previous work, we expect to observe the self-regulation of star formation (Zaragoza-Cardiel et al. 2019), and it allows us to include galaxies at distances of up to 100

\[^1\] http://leda.univ-lyon1.fr/fullsql.html
\[^2\] http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form?collection_name=MUSE
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Table 1. Galaxy sample.

| Galaxy identifier | PGC identifier | $D$ (Mpc) | $z$ | Type | $i$ |
|-------------------|----------------|----------|-----|------|-----|
| pgc33816          | PGC33816       | 23.6     | 0.005187 | 7.0 | 19.9 |
| eso184-g082       | PGC63387       | 35.2     | 0.00667 | 4.1 | 32.6 |
| eso467-062        | PGC68883       | 57.5     | 0.013526 | 8.6 | 49.9 |
| ugc272            | PGC1713        | 55.6     | 0.012993 | 6.0 | 70.7 |
| ngc5584           | PGC51344       | 51.3     | 0.006464 | 5.9 | 42.4 |
| eso319-g015       | PGC34856       | 37.5     | 0.009159 | 8.6 | 54.2 |
| ugc11214          | PGC61802       | 38.0     | 0.008903 | 5.9 | 16.5 |
| ngc6118           | PGC57924       | 20.5     | 0.005247 | 6.0 | 68.7 |
| ic1158            | PGC56723       | 24.5     | 0.006288 | 5.1 | 62.2 |
| ngc5468           | PGC50323       | 30.0     | 0.009489 | 6.0 | 21.1 |
| esos25-g045       | PGC50055       | 75.9     | 0.017842 | 7.0 | 40.2 |
| ngc1954           | PGC17422       | 38.0     | 0.010441 | 4.4 | 61.5 |
| ic5332            | PGC71775       | 9.9      | 0.002338 | 6.8 | 18.6 |
| ugc04729          | PGC25309       | 57.0     | 0.013009 | 6.0 | 35.2 |
| ngc2104           | PGC17822       | 16.4     | 0.003673 | 8.5 | 83.6 |
| esos316-g7        | PGC28744       | 47.5     | 0.01166  | 3.3 | 70.0 |
| esos209-g28       | PGC88771       | 70.1     | 0.016895 | 3.8 | 64.4 |

$^a$ Principal General Catalog of Galaxies identifier from Hyperleda database (Paturel et al. 2003). $^b$ Distance from the $z=0$ Multi-wavelength Galaxy Synthesis (z0MGS from Leroy et al. (2019), when available) and HyperLeda database best homogenized distances (Makarov et al. 2014). $^c$ Redshift, from Nasa Ned. $^d$ Numerical morphological type, from the HyperLeda database. $^e$ Inclination from the HyperLeda database.

Mpc where 500 pc corresponds to 1 arcsec. We also need the foreground stars to be masked. We extract the spectrum for each defined region, correct it for Galactic extinction, and associate each with a redshift estimate, using the H$_\alpha$ or [NII] at 6583.4 if the later has a stronger peak than the former. We next estimate the [NII]/H$\alpha$ and [OIII]/H$\beta$ flux ratios, and remove the regions which are classified as Seyfert-LINER in the BPT diagram (Kewley et al. 2006).

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3 STELLAR POPULATION SYNTHESIS AND MODEL FITS

3.1 Stellar population synthesis

We use SINOPSIS code 3 (Fritz et al. 2007, 2017) to fit combinations of SSPs to the observed spectra. SINOPSIS fits equivalent widths of emission and absorption lines, as well as defined continuum bands. In this work, we use the Hα and Hβ equivalent widths, and the 9 continuum bands shown in Fig. 2, where we show two observed spectra of the galaxy NGC 716 and the resulted fits as an example.

3 https://www.iry.a.unam.mx/gente/j.fritz/JFhp/SINOPSIS.html
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We use the updated version of the Bruzual & Charlot models (Werle et al. 2019). We used SSPs of 3 metallicities (Z = 0.004, Z = 0.02, and Z = 0.04) in 12 age bins (2 Myr, 4 Myr, 7 Myr, 20 Myr, 57 Myr, 200 Myr, 570 Myr, 1 Gyr, 3 Gyr, 5.75 Gyr, 10 Gyr, and 14 Gyr). We assume a free form of SFH, the Calzetti dust attenuation law (Calzetti et al. 2000), and the Chabrier 2003 IMF (Chabrier 2003) for stellar masses between 0.1M⊙ and 100M⊙. The emission lines for the SSPs younger than 20 Myr are computed using the photoionisation code CLOUDY (Ferland 1993; Ferland et al. 1998, 2013), assuming case B recombination (Osterbrock 1989), an electron temperature of 10^4K, an electron density of 100cm^-3, and a gas cloud with an inner radius of 10^-3pc (Fritz et al. 2017).

SINOPSIS uses the degeneracies between age, metallicity, and dust attenuation, to compute the uncertainties in the derived parameters (Fritz et al. 2007).

In order to use regions with a meaningful result, we take into account only regions with a signal to noise ratio (SNR) larger than 20 over the [5350 – 5420] range, and χ^2 < 3. Due to IMF sampling effects, we also consider only regions where the recent SFR is larger than 10^{-3}M⊙/yr and the past SFR is larger than 10^{-5}M⊙/yr.

Because we are limited to galaxies from Hubble Type Sa to Sdm, also excluding interacting galaxies and (U)LIRGs, the galaxy sample, by construction, is defined by galaxies that are probably on the star formation galaxy main sequence, and probably evolved via secular evolution in the studied age range (last 570 Myr), where by secular evolution we mean evolution dominated by slow processes (slower than many galaxy rotation periods Kormendy & Kennicutt (2004)). The galaxies probably evolved through more violent episodes in the past, but we are not affected by them in the studied age range. Nevertheless, individual zones such as the centres of the galaxies, might have evolved via rapid evolution due to high gas flows even in the studied age range. Because of this, we removed regions whose centres are at a distance of 500 pc or less from the centre of the galaxy, as well as regions having a very high recent SFR compared to the rest of the galaxy, specifically, we removed regions having ΣSFR_recent larger than ΣSFR_recent + 3σΣSFR_recent for each galaxy. We will discuss how affects the results the removal of very high recent SFR regions in the discussion section (§6.4).

3.2 Fitting data to self-regulator the model

We have made the same assumptions made in Zaragoza-Cardiel et al. (2019) in order to fit our observables to the self-regulator model. For completeness, we briefly describe them here.

The self-regulator model (Eq. 2) is valid for a star or a group of co-rotating stars in the galaxy such as a massive star cluster (>500M⊙ Lada & Lada (2003)). Assuming η constant, Eq. 2 is linear, so we can add up regions obeying that equation, and still obey the equation. In this context, the

Figure 1. Colour composite RGB image recovered from MUSE data of one of the studied galaxies, UGC 11001. The red, green and blue images used to create RGB are obtained by integrating MUSE spectra in R, V and B filters, respectively. 500pc wide regions where spectra was extracted are overplotted as green and the regions identified as those on the envelope (defined above in section §4) are marked as red squares.

Figure 2. Two characteristic spectra for the galaxy NGC 716. Observed spectra are shown as blue lines. Top: the total star formation is dominated by the past star formation. Bottom: the total star formation is dominated by the recent star formation. The model spectrum which best fits the observed spectrum is shown as a red line. The continuum bands used to fit the observed spectrum to the combination of SSPs are shown as black lines.

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mass-loading factor would be representative of massive star clusters scales ($\sim$pc Lada & Lada (2003)). Although we find below that $\eta$ varies (Eq. 6), the variation is smooth enough to consider it approximately constant here. Therefore, the group of stars which are massive enough to produce bound clusters can be considered as a whole, while the less massive ones are split into individual stars. Feedback between different regions is then not considered here. We assume that our 500 pc wide regions are made of individual smaller regions obeying Eq. 2, so we can rewrite Eq. 2 to be valid for our larger regions as the average of individual regions:

$$\dot{\Sigma}_{\text{gas}} = \dot{\Sigma}_{\text{net,flow}} - \Sigma_{\text{SFR}}(1 - R + \eta).$$ \hspace{1cm} (4)

We already showed in Zaragoza-Cardiel et al. (2019) that the resulted mass-loading factor was independent of the chosen scale (from 87pc to 1kpc) in NGC 628. Hence, regions can be added up while Eq. 4 is still valid.

The value of the $\Sigma_{\text{SFR, past}}$ we are able to measure is a time average over 550 Myr. Since Eq. 4 is linear, we can substitute the time differentials by time average values over our age bin, and we will not be affected by possible bursts of the star formation, as long as the variation of $\eta$ is small enough (as we do find below).

The net gas flow rate surface density, $\dot{\Sigma}_{\text{net,flow}}$, is the change in gas density due to gas flows (independently of star formation), which can be negative, although in that case, the star formation is quenched (Zaragoza-Cardiel et al. 2019). This term, $\dot{\Sigma}_{\text{net,flow}}$, also includes the possibility of gas return from different regions and the same region at a later epoch, an effect known as galactic fountains (Fraternali 2017). The observables are $\Sigma_{\text{SFR, recent}}$ and $\Sigma_{\text{SFR, past}}$. Let us assume that we can estimate $\dot{\Sigma}_{\text{gas}}$ from the star formation change considering the KS law, $\Sigma_{\text{SFR, past}} = A\Sigma_{\text{gas}, \text{past}}$, and rewrite Eq. 2:

$$\Sigma_{\text{SFR, recent}} = A\left[\frac{\dot{\Sigma}_{\text{net,flow}} - \Sigma_{\text{SFR, past}}(1 - R + \eta)}{A}\right] \Delta t + \left[\frac{\Sigma_{\text{SFR, past}}}{A}\right]^N. \hspace{1cm} (5)$$

where there is a relation between our two observables ($\Sigma_{\text{SFR, recent}}$ and $\Sigma_{\text{SFR, past}}$), $\dot{\Sigma}_{\text{net,flow}}$, and $\eta$. We will use a simplistic approximation to estimate $\dot{\Sigma}_{\text{net,flow}}$, since we do not observe it. As explained in Zaragoza-Cardiel et al. (2019), we assume that several regions have an approximate value close to the maximum value of $\dot{\Sigma}_{\text{net,flow}}$, for a given galaxy. In the case of the estimation of $\eta$, although $\eta$ could vary between regions, we will find that the variation is smooth enough (Eq. 6) to consider the existence of a representative value for specific regions. In the following, for simplicity since we are only dealing with one type of regions, the 500 pc wide ones, we will use the analysed terms (e.g. $\Sigma_{\text{SFR, recent}}$, $\Sigma_{\text{SFR, past}}$, and $\dot{\Sigma}_{\text{net,flow}}$) without the need of using the average symbols ($\Sigma_{\text{SFR, recent}}$, $\Sigma_{\text{SFR, past}}$, $\dot{\Sigma}_{\text{net,flow}}$). Therefore, when we present an average, the average will be for several 500 pc wide regions.

Assuming the instantaneous recycling approximation (Madau & Dickinson 2014) for stars more massive than $3M_{\odot}$ ($t_{\text{MS}} \sim 0.6$ Gyr, where $t_{\text{MS}}$ is the main sequence lifetime), and a Chabrier IMF (Chabrier 2003), we obtain a value of the net gas flow rate surface density, $\dot{\Sigma}_{\text{net,flow}}$, \(\eta = 2.5 \pm 0.1\). We use the values $A = 10^{-4.32} M_{\odot}/kpc^2/yr$, and $N = 1.56$ for the KS law (Kennicutt et al. 2007).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Recent star formation rate surface density, $\Sigma_{\text{SFR, recent}}$, versus the past star formation rate surface density, $\Sigma_{\text{SFR, past}}$, for the UGC 11001 galaxy. The red dots are the regions identified as those on the envelope. We plot the fit of Eq. 5 to the regions on the envelope as well as the result of the fit and the 1-$\sigma$ uncertainty range of the fit as shaded region.}
\end{figure}

4 RESULTS

As an example, we plot the $\Sigma_{\text{SFR, recent}}$ versus $\Sigma_{\text{SFR, past}}$ diagram for one of the galaxies, UGC 11001, in Fig. 3. We plot the $\Sigma_{\text{SFR, recent}}$ versus $\Sigma_{\text{SFR, past}}$ diagrams for all of the galaxies in Fig. A1. Each of the points in these plots can be seen as the relation between the $\Sigma_{\text{SFR, recent}}$ and $\Sigma_{\text{SFR, past}}$ which depends on the value of $\dot{\Sigma}_{\text{net,flow}}$, and $\eta$ (Eq. 5).

We identify those regions having the maximum $\Sigma_{\text{SFR, recent}}$, per bin of $\Sigma_{\text{SFR, past}}$, as the regions on the envelope. We see the regions on the envelope as red dots in Fig. 3, and as red squares in the MUSE recovered false color image of UGC 11001 in Fig. 1.

We can see in Eq. 5 that we need the value of $\dot{\Sigma}_{\text{net,flow}}$ in combination with the $\Sigma_{\text{SFR, recent}}$ and $\Sigma_{\text{SFR, past}}$ values, in order to quantity $\eta$. For a given galaxy, there should be a maximum value for the net flow gas surface density term, $\dot{\Sigma}_{\text{flow, max}}$. Although in principle $\dot{\Sigma}_{\text{flow, max}}$ is unknown for us, if we assume that there are several segments where $\dot{\Sigma}_{\text{net,flow}} \sim \dot{\Sigma}_{\text{flow, max}}$, then these regions are those on the $\Sigma_{\text{SFR, recent}}$ versus $\Sigma_{\text{SFR, past}}$ diagram envelope.

Assuming $\dot{\Sigma}_{\text{net,flow}}$ constant, we fit Eq. 5 to the regions on the envelope and estimate the mass-loading factor, representative of those specific regions. We have selected a galaxy sample mainly composed by galaxies on the main sequence of star formation, and remove segments having very high $\Sigma_{\text{SFR, recent}}$ compared to the rest of the segments of a galaxy. Therefore, the galaxy sample, as well as the segments, have been chosen to assure the $\dot{\Sigma}_{\text{net,flow}} \sim \dot{\Sigma}_{\text{flow, max}}$ hypothesis for several regions. The regions below the envelope are due, to a greater extent, to regions having a smaller value of $\eta$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Recent star formation rate surface density, $\Sigma_{\text{SFR, recent}}$, versus the past star formation rate surface density, $\Sigma_{\text{SFR, past}}$, for the UGC 11001 galaxy. The red dots are the regions identified as those on the envelope. We plot the fit of Eq. 5 to the regions on the envelope as well as the result of the fit and the 1-$\sigma$ uncertainty range of the fit as shaded region.}
\end{figure}
Table 2. Estimated mass-loading factors, $\eta$, maximum flow gas surface density term, $\Sigma_{\text{flow max}}$, and the associated average stellar mass surface density for the regions on the envelope, $\Sigma_*$.

| Galaxy identifier | $\eta$ | $\Sigma_{\text{flow max}}$ | $\Sigma_*$ |
|------------------|-------|-----------------|--------|
| pgc33816         | 4.8 ± 0.9 | 4.9 ± 0.9     | 27 ± 15 |
| eso184-g082      | 5.0 ± 1.0 | 8.7 ± 0.6     | 49 ± 20 |
| eso467-062       | 8.0 ± 2.0 | 14.0 ± 1.0    | 51 ± 39 |
| ugc272           | 3.4 ± 0.2 | 6.9 ± 0.4     | 57 ± 44 |
| ngc5584          | 2.2 ± 0.4 | 4.0 ± 1.0     | 60 ± 31 |
| eso319-g015      | 5.0 ± 2.0 | 11.0 ± 3.0    | 66 ± 65 |
| ugc11214         | 2.6 ± 0.6 | 9.0 ± 2.0     | 84 ± 33 |
| ngc6118          | 2.19 ± 0.09 | 2.8 ± 0.3    | 90 ± 51 |
| ic1158           | 6.8 ± 0.4 | 16.3 ± 0.3    | 109 ± 28 |
| ngc5468          | 2.2 ± 0.8 | 23.0 ± 2.0    | 113 ± 66 |
| eso325-g045      | 1.7 ± 0.2 | 12.0 ± 1.0    | 121 ± 57 |
| ngc1954          | 3.3 ± 0.5 | 23.8 ± 0.8    | 121 ± 31 |
| ic5332           | 3.0 ± 1.0 | 12.0 ± 2.0    | 120 ± 100 |
| ugc64729         | 2.8 ± 0.6 | 7.0 ± 2.0     | 126 ± 57 |
| ngc2104          | 1.7 ± 0.6 | 4.0 ± 2.0     | 132 ± 62 |
| eso316-g7        | 2.0 ± 1.0 | 12.0 ± 6.0    | 136 ± 39 |
| ugc298-g28       | 6.0 ± 0.7 | 47.0 ± 2.0    | 136 ± 46 |
| mcg-01-57-021    | 7.0 ± 1.0 | 17.0 ± 2.0    | 137 ± 24 |
| pgc128348        | 2.9 ± 0.1 | 11.6 ± 0.7    | 140 ± 92 |
| pgc1167400       | 2.3 ± 0.3 | 4.1 ± 0.8     | 141 ± 78 |
| ngc2835          | 2.2 ± 0.7 | 7.0 ± 3.0     | 144 ± 40 |
| ic2151           | 2.0 ± 0.5 | 5.0 ± 3.0     | 146 ± 61 |
| ngc988           | 1.2 ± 0.4 | 1.0 ± 2.0     | 158 ± 6 |
| ngc1483          | 3.0 ± 2.0 | 13.0 ± 5.0    | 158 ± 40 |
| ngc7421          | 1.1 ± 0.3 | 1.0 ± 0.9     | 167 ± 78 |
| fcc290           | 2.0 ± 0.4 | 3.0 ± 1.0     | 169 ± 42 |
| ic344            | 2.5 ± 0.2 | 11.0 ± 1.0    | 171 ± 78 |
| ngc3389          | 4.4 ± 0.7 | 32.4 ± 0.7    | 190 ± 130 |
| eso246-g21       | 2.9 ± 0.7 | 7.0 ± 2.0     | 188 ± 67 |
| pgc170248        | 4.9 ± 0.7 | 16.0 ± 1.0    | 192 ± 77 |
| ngc7229          | 4.1 ± 0.2 | 7.8 ± 0.4     | 200 ± 120 |
| ugc12859         | 2.8 ± 0.3 | 5.1 ± 0.9     | 202 ± 90 |
| ugc1395          | 2.7 ± 0.3 | 8.0 ± 1.0     | 200 ± 160 |
| ngc5539          | 2.9 ± 0.4 | 5.0 ± 1.0     | 210 ± 150 |
| ngc1591          | 2.3 ± 0.7 | 19.0 ± 4.0    | 212 ± 93 |
| pgc98793         | 1.7 ± 0.1 | 6.6 ± 0.8     | 214 ± 95 |
| ugc5378          | 2.7 ± 0.4 | 10.0 ± 1.0    | 223 ± 93 |
| ngc4880          | 1.9 ± 0.2 | 10.3 ± 0.9    | 230 ± 170 |
| ngc1087          | 1.3 ± 0.3 | 14.0 ± 2.0    | 230 ± 170 |
| ngc1980          | 1.8 ± 0.3 | 6.6 ± 0.9     | 240 ± 170 |
| ngc6902          | 2.4 ± 0.3 | 8.0 ± 1.0     | 240 ± 13 |
| ugc11001         | 2.5 ± 0.1 | 21.8 ± 5.0    | 250 ± 140 |
| ic217            | 1.2 ± 0.4 | 3.0 ± 2.0     | 266 ± 88 |
| eso306-g004      | 3.4 ± 0.2 | 13.9 ± 4.0    | 270 ± 170 |
| ic2160           | 2.4 ± 0.4 | 12.0 ± 2.0    | 270 ± 260 |
| ngc1385          | 0.9 ± 0.1 | 9.7 ± 0.9     | 272 ± 44 |
| mcg-01-33-034    | 1.0 ± 0.09 | 7.9 ± 0.5    | 270 ± 150 |
| ngc4693          | 0.9 ± 0.1 | 3.0 ± 1.0     | 276 ± 85 |
| ngc4535          | 4.1 ± 0.7 | 15.0 ± 2.0    | 280 ± 200 |
| ngc1762          | 2.3 ± 0.2 | 8.2 ± 0.7     | 290 ± 140 |
| ngc3451          | 3.7 ± 0.4 | 11.0 ± 1.0    | 300 ± 180 |
| ngc4790          | 1.2 ± 0.3 | 9.0 ± 2.0     | 334 ± 63 |
| ngc3424          | 1.8 ± 0.2 | 8.0 ± 1.0     | 340 ± 270 |
| ngc628           | 1.8 ± 0.1 | 19.0 ± 1.0    | 360 ± 170 |
| pgc3051         | 0.7 ± 0.4 | 0.0 ± 2.0     | 360 ± 160 |
| ngc5643          | 1.1 ± 0.3 | 3.0 ± 2.0     | 410 ± 160 |
| ngc1309         | 1.3 ± 0.2 | 17.0 ± 2.0    | 420 ± 220 |

$\eta$ Mass-loading factor derived in this work. $\Sigma_{\text{flow max}}$ Maximum flow gas surface density term derived in this work. $\Sigma_*$ Stellar mass surface density for the regions on the envelope obtained in this work.

$\Sigma_{\text{net flow}} < \Sigma_{\text{flow max}}$, and to a much lesser extent, to regions having different $\eta$ values.

We have fitted Eq. 5 to the envelopes of the 102 galaxy listed in Table 1 and show the results in Fig. 3 for UGC 11001, and in Fig. A1 for the rest of the galaxies, as a red line.

4.1 Variations of $\eta$

Although we have an $\eta$ value for each galaxy, $\eta$ is an average value representative only of the regions on the envelope, instead of the whole galaxy. We associate the estimated $\eta$ for a given envelope with the average surface stellar mass density, $\Sigma_*$, of those regions on the envelope where we esti-
5 LOCAL TO GLOBAL MASS-LOADING FACTORS

The mass-loading factor derived here is representative of local scales. However, other observational and theoretical studies report global mass-loading factors (Muratov et al. 2015; Rodriguez-Puebla et al. 2016; Hayward & Hopkins 2017; Schroetter et al. 2019; McQuinn et al. 2019). We estimate global mass-loading factors, \( \eta_G \), from the empirical \( \eta - \Sigma \) relation reported here (Eq. 6), integrating over observed stellar mass density profiles.

To convert \( \eta \) to \( \eta_G \), we assume that we can estimate the total outflow due to stellar feedback, \( \dot{M}_{\text{out}} \), by adding up \( \Sigma_{\text{out}} \) over each individual segment where stellar feedback acts. Since we are interested in galaxy discs, we assume a radial characterization for the properties of interest, i.e., \( \Sigma, \Sigma_{\text{out}}, \Sigma_{\text{SFR}}, \) and \( \Sigma_{\text{SFR}} \) depend on \( R \), the radial distance to the centre of the disc:

\[
\eta_G = \frac{\dot{M}_{\text{out}}}{\text{SFR}} = \frac{\int_0^\infty \Sigma_{\text{out}}(R) R dR}{\int_0^\infty \Sigma_{\text{SFR}}(R) R dR} = \frac{\int_0^\infty \eta(R) \Sigma_{\text{SFR}}(R) R dR}{\int_0^\infty \Sigma_{\text{SFR}}(R) R dR}.
\]

(7)

The conversion between \( \eta \) to \( \eta_G \) is a local-averaged property, which depends on a mean stellar mass density over a range of radii. Stellar mass density profiles, \( \Sigma(R) \), are better constrained than \( \Sigma_{\text{SFR}}(R) \) profiles, so we decide to use the empirical relation between \( \Sigma_{\text{SFR}} \propto \Sigma^p \). For simplicity, we assume \( p = 1 \), which is consistent with the latest results of this relation for galaxy discs (Cano-Díaz et al. 2019), although we found that different \( n \) values close to 1 do not change the results significantly. Using our empirical relation (Eq. 6) we rewrite Eq. 7:

\[
\eta_G = \frac{\int_0^\infty \eta(R) \Sigma(R) R dR}{\int_0^\infty \Sigma(R) R dR} = 10^{3.2} \frac{\int_0^\infty \Sigma(R)^{0.68} R dR}{\int_0^\infty \Sigma(R) R dR}.
\]

(8)

The stellar mass surface density profile, \( \Sigma(R) \), is therefore all we need to compute the global mass-loading factor. We use the deepest stellar mass surface density profiles from the Spitzer Survey of Stellar Structure in Galaxies (S4G) (Díaz-García et al. 2016) to compute the global mass-loading factor as a function of stellar mass. S4G stellar mass surface density profiles are divided into 5 mass bins: \( [10^{9.5} - 10^{10}] \), \( [10^{10} - 10^{10.5}] \), \( [10^{10.5} - 10^{11}] \), \( [10^{11} - 10^{11.5}] \), and \( [10^{11.5} - 10^{12}] \) M\(_{\odot}\). We used these 5 mass bins to compute the \( \eta_G \) shown in Fig. 5.

5.1 Variations of \( \eta_G \)

We present our empirically derived global mass-loading factors as a function of stellar mass in Fig. 5 as black lines. The discontinuity is due to the division in different parameterizations of the stellar mass surface density profiles in 5 mass
6 DISCUSSION

6.1 Comparison with other studies

The results reported here are slightly different when we compare them with recent observational studies reporting local (Kruĳssen et al. 2019; Roberts-Borsani et al. 2020) and global (Schroetter et al. 2019; McQuinn et al. 2019) mass-loading factors.

The reported local mass-loading factors using the spatial de-correlation between star formation and molecular gas (Kruĳssen et al. 2019) differ by less than 3σ from our reported values, and it might be due to the smaller time scale of ~ 1.5 Myr for which they report efficient gas dispersal, while our reported time scale is ~ 500 Myr. The previously reported local mass-loading factors using the Na D absorption (Roberts-Borsani et al. 2020) are consistent with ours within 1σ.

The use of Mg II absorption of the circum-galactic medium to derive global mass-loading factors gives no clear dependence on the total mass of the galaxy (Schroetter et al. 2019). However, the Mg II absorption method gives σG with very high uncertainties, mainly due to the uncertainty when deriving the HI column density from the Mg II equivalent width (Schroetter et al. 2015). Due to these large uncertainties, their results are apparently consistent with our results within 1σ for most of their reported σG’s.

The mass-loading factor estimates using deep Hα imaging give smaller mass-loading factors compared to those reported here and give no correlation with the stellar mass of the galaxy (McQuinn et al. 2019). Nevertheless, the method using Hα imaging derives the amount of outflowing gas from the Hα surface brightness background, so it neglects Hα emission stronger than this background emission. The estimated outflowing mass could be inferior to the real one since we already know that Hα emission has a component due to expansive bubbles (Relaño & Beckman 2005; Camps-Fariña et al. 2015).

6.2 Discussion on envelope’s shapes

Eq. 5 depends on Σflow max, η, ΣSFR recent, and ΣSFR past values. The case shown in Fig. 3, where there is no high recent star formation rate for those regions where the past star formation rate was the highest, is a common case, but not the only one. For instance, there are cases where ΣSFR recent values are approximately constant through the regions on the envelope or even increase as ΣSFR past increase (e.g. NGC 988, NGC 7421, IC 217, IC 4452, PGC 28308 in Fig. A1).

Essentially, there are two terms depending on ΣSFR past in Eq. 5, one with a direct proportionality and the other with an inverse one. The latter dominates for larger η values meaning that the larger the mass-loading factor, the larger is the effect in reducing the amount of gas to form stars, as expected. However, for small enough η and ΣSFR past values, the directly dependent term can dominate producing a direct relation between ΣSFR recent and ΣSFR past, as we see in some galaxies in Fig. A1 (e.g. IC 4452). The extrapolation of Eq. 5 to large enough values of ΣSFR past would give always a decrease in ΣSFR recent, as long as η > 0, and that is the reason to observe some inverted U-shape envelopes (e.g. NGC 1084, PGC 3140).
Finally, for large enough $\Sigma_{\text{flow max}}$ values, the directly $\Sigma_{\text{SFR past}}$ dependent term is almost negligible for small values of $\Sigma_{\text{SFR past}}$, and then the recent star formation depends on $\Sigma_{\text{flow max}}$ for the low $\Sigma_{\text{SFR past}}$, while it decreases proportionally with $\Sigma_{\text{SFR past}}$ depending on the mass-loading factor (e.g. UGC 5378, UGC 11001).

Therefore, the combination of $\Sigma_{\text{flow max}}$ and $\eta$ variations, as well as the range covered by the past and recent star formation rate surface densities, is what gives different envelope’s shapes. The uncertainties obtained when fitting Eq. 5 show reliable estimates, except for one case, the PGC 30591 galaxy, which is the one having the highest inclination of our sample.

### 6.3 High-inclination galaxies

Although we have removed edge-on ($i = 90^\circ$) galaxies from our sample, high-inclination ($i > 70^\circ$) galaxies might not be good candidates to apply the method used in this study, as in the case of the PGC 30591 galaxy. In the case of edge-on and very high-inclination galaxies, two main effects can affect the pertinence of applying the method. Firstly, one can have in the line of sight a large combination of different regions of the galaxy. Secondly, the higher the inclination, the smaller is the number of resolved regions, while the method relies on a large enough number of resolved regions.

Nevertheless, except for PGC 30591, we found reliable $\Sigma_{\text{flow max}}$ and $\eta$ estimates, even for high-inclination galaxies. Including or excluding high-inclination galaxies does not make any changes to the reported $\eta-\Sigma_*$ relation presented here. We show in Fig. 6 the $\eta-\Sigma_*$ observed and fitted relations for high-inclination galaxies, as star symbols and black line, respectively. When we compare the high-inclination galaxies results with the fit obtained using the full sample (Eq. 6), shown as a red line, both samples are compatible within 1σ.

### 6.4 Effects of very high recent SFR regions removal

We think is important to remove regions having very high values of $\Sigma_{\text{SFR recent}}$ compared to the rest of the galaxy, since these regions probably have a very high $\Sigma_{\text{net flow}}$ value compared to the rest of the regions identified to be on the envelope. The effect of considering these high $\Sigma_{\text{SFR recent}}$ regions affects our assumption about the approximate equal value of $\Sigma_{\text{net flow}}$ for the regions on the envelope.

However, in order to explore the effect of this removal in our results, we have performed the same analysis without removing any region based on its $\Sigma_{\text{SFR recent}}$ value. We plot the derived $\eta$ versus the local $\Sigma_*$ of the regions on the envelope for the whole sample of galaxies in Fig. 7. We also plot the resulted $\eta-\Sigma_*$ fit to the observed data. We find a very similar correlation between $\eta$ and the local $\Sigma_*$:

$$\log(\eta + 1) = (-0.32 \pm 0.05)\log(\Sigma_*) + (3.2 \pm 0.4).$$  \hspace{1cm} (9)

There are only 4 galaxies where the $\eta$ value significantly changes: IC 1158, NCG 3389, ESO 298-G28, and MCG 01-57-021. We marked these galaxies as orange circles in Fig. 7. However, the changes are not significant enough to change the resulted $\eta-\Sigma_*$ relation, but just a slightly increase in the obtained uncertainties. Therefore, although the removal could be important for some specific individual galaxies, when compared with the full sample of galaxies we still find a consistent $\eta-\Sigma_*$ relation.
7 CONCLUSIONS

We have used MUSE observations of a sample of 102 galaxy discs. We extracted the spectra of 500 pc wide regions and apply them stellar population synthesis using SINOPSIS code. We obtained the star formation histories of those regions and we analysed the recent and past star formation rate densities. We compared the $\Sigma_{\text{SFR, past}}$ with the $\Sigma_{\text{SFR, recent}}$ and found that, for each galaxy, there is an envelope of regions formed by those regions having the maximum $\Sigma_{\text{SFR, recent}}$ per bin of $\Sigma_{\text{SFR, past}}$. We fitted the resolved star formation self-regulator model (Eq. 5) to those regions on the envelope and quantify the mass-loading factor, $\eta$.

We find correlations locally between $\eta$ and the stellar mass surface density, $\Sigma_*$, and generally between the averaged value of $\eta$ for a galaxy, $\eta_G$, and the stellar mass of the galaxy, $M_*$, which are strong indications of how stellar feedback locally regulates the mass growth of galaxies, especially those of lower masses. The comparison between our empirical local $\eta$-$\Sigma_*$ relation with that from hydrodynamical simulations of supernova explosions (Li et al. 2017) is remarkably in agreement. In the case of our empirical global $\eta_G$-$M_*$ relation, the comparison with hydrodynamical cosmological zoom-in galaxy simulations (Muratov et al. 2015) is also in excellent agreement.

We note that the value of $\eta$ depends on the time scale over which the feedback is analysed, and can be defined either including or excluding posterior gas return, so comparison with other observations and with theory must be done with care. These empirical relations offer excellent tools to confront with stellar feedback models which are crucial for understanding galaxy formation and evolution.

ACKNOWLEDGEMENTS

The authors thank the anonymous referee whose comments have led to significant improvements in the paper. The authors also thank Aldo Rodríguez-Puebla for sharing their stellar halo accretion rate coevolution models from Rodríguez-Puebla et al. (2016). JZC and IA’s work is funded by a CONACYT grant through project FDC-2018-1848. DRG acknowledges financial support through CONACYT project A1-S-22784. GB acknowledges financial support through PAPIIT project IG100319 from DGAPA-UNAM. Stephentown’s work is supported by a CONACYT grant through project FDC-2018-1848. SFRP acknowledges financial support through CONACyT grant through project A1-S-22784. GB acknowledges financial support through CONACyT grant through project FDC-2018-1848.

REFERENCES

Arp H., 1966, ApJS, 14, 1
Ascasibar Y., Gavilán M., Pinto N., Casado J., Rosales-Ortega F., Díaz A. I., 2015, MNRAS, 448, 2126
Astropy Collaboration et al., 2013, A&A, 558, A33
Astropy Collaboration et al., 2018, AJ, 156, 123
Bacon R., et al., 2010, in Proc. SPIE. p. 77508, doi:10.1117/12.856027
Barrera-Ballesteros J. K., et al., 2018, ApJ, 852, 74
Barrera-Ballesteros J. K., et al., 2020, MNRAS, 492, 2651
Behroozi P. S., Conroy C., Wechsler R. H., 2010, ApJ, 717, 379
Bigel F., Leroy A., Walter F., Brinks E., de Blok W. J. G., Madore B., Thornley M. D., 2008, AJ, 136, 2846
Bouchet N., et al., 2010, ApJ, 718, 1001
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Camps-Farína A., Zaragoza-Caridi J., Beckman J. E., Font J., García-Lorenzo B.,Erroz-Ferrer S., Amram P., 2015, MNRAS, 447, 3840
Cano-Díaz M., Ávila-Reese V., Sánchez S. F., Hernández-Toledo H. M., Rodríguez-Puebla A., Boquien M., Ibarra-Medel H., 2019, MNRAS, 488, 3929
Chabrier G., 2003, PASP, 115, 763
Cid Fernandes R., Mateus A., Sodré L., Stasińska G., Gomes J. M., 2005, MNRAS, 358, 363
Creasey P., Theuns T., Bower R. G., 2013, MNRAS, 429, 1922
Dekel A., Mandelker N., 2014, MNRAS, 444, 2071
Díaz-García S., Salo H., Laurikainen E., 2016, A&A, 596, A84
Erroz-Ferrer S., et al., 2019, MNRAS, 484, 5009
Ferland G. J., 1993, Hazy, A Brief Introduction to Cloudy 84
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, PASP, 110, 761
Ferland G. J., Kiseliušis R., Keenan F. P., van Hoof P. A. M., 2014, MNRAS, 493, 4466
Fraternali F., 2017, Gas Accretion via Condensation and Fountains. p. 323, doi:10.1007/978-3-319-52512-9_14
Fritz J., et al., 2007, A&A, 470, 137
Fritz J., et al., 2011, A&A, 526, A45
Fritz J., et al., 2017, ApJ, 848, 132
Ginsburg A., et al., 2019, AJ, 157, 98
Hayward C. C., Hopkins P. F., 2017, MNRAS, 465, 1682
Hopkins P. F., 1992, ApJ, 255, 392
Hopkins P. F., Kereı̈ D., Oñorbe J., Faucher-Giguère C.-A., Quataert E., Murray N., Bullock J. S., 2014, MNRAS, 445, 581
Hopkins P. F., et al., 2018, MNRAS, 480, 800
Kennicutt Robert C. J., et al., 2007, ApJ, 671, 333
Kewley L. J., Groves B., Kauffmann G., Heckman T., 2006, MNRAS, 368, 768
Kormendy J., Kennicutt Robert C. J., 2004, ARA&A, 42, 603
Kriek K., et al., 2019, ApJ, 887, 80
Kruijssen J. M. D., et al., 2019, Nature, 569, 519
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Leroy A. K., et al., 2019, ApJS, 244, 24
Li M., Bryan G. L., Ostriker J. P., 2017, ApJ, 841, 101
DATA AVAILABILITY

The data underlying this article are available in the ESO archive, at http://archive.eso.org/. The datasets were derived for each source through the query form at http://archive.eso.org/wdb/wdb/adp/phase3_spectral/form?collection_name=MUSE.

APPENDIX A: SFR RECENT-PAST DIAGRAMS
Figure A1. SFR recent-past diagrams. Recent star formation surface density, $\Sigma_{\text{SFR, recent}}$, versus the past star formation rate surface density, $\Sigma_{\text{SFR, past}}$, for each galaxy of the sample. The red dots are the regions identified as those on the envelope. We plot the fit of Eq. 5 to the regions on the envelope and the 1-$\sigma$ uncertainty range of the fit as shadow region. We show the parameters of the fit, at the top of each panel.
Figure A1 – continued
Figure A1 – continued

Stellar feedback locally regulates galaxy growth
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Stellar feedback locally regulates galaxy growth

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