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EVOLUTION OF DISC GALAXIES USING THE VOLUMETRIC STAR FORMATION LAW

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Abstract

Cold gas is the fuel for star formation and thus essential for studying galaxy formation and evolution. However, it has been shown that the gas reservoir of present-day galaxies is insufficient to sustain star formation for a long time. Therefore, gas accretion from the external environment is necessary. Fraternali & Tomassetti (2012) developed an analytical model for the evolution of a disc galaxy to estimate the gas accretion rate as a function of time in a sample of present-day spiral galaxies. In this thesis, we expand on the model of Fraternali & Tomassetti (2012) by implementing a novel star formation law linking the gas and the star formation rate (SFR) volume densities. This is the volumetric star formation (VSF) law, which has a different shape than the Kennicutt relation used previously, with a crucial impact on the gas accretion profile required to sustain star formation. In particular, we explore the effect of changing the star formation law on the evolution of the Milky Way.

We find that, by adopting the VSF law, the gas accretion is slightly increased over the whole star-forming disc compared to the model based on the Kennicutt law, but otherwise similar. We find the gas accretion has decreased over time, especially in the inner galaxy. Using two-dimensional maps of the gas accretion rate in the galaxy, we see signs of flaring in the outskirts and that the central region of gas accretion shifts more towards the outskirts over time, until it reaches near null presently.

Contents

Chapter 1

Introduction

Star formation plays a key role in the build-up of stellar mass for a galaxy across cosmic time. The fuel for star formation is cold gas, implying that the cold gas reservoir of galaxies must be refilled in some way to replace the mass converted and locked into stars.

The depletion time is the time required to exhaust the cold gas reservoir of a galaxy, implying that the galaxy can no longer form stars. The depletion time for star-forming galaxies is approximately 1 Gyr (Saintonge et al., 2011). This timescale is much smaller than the lifetime of present-day disc galaxies like the Milky Way, which is approximately 10 *Gyr* old. This discrepancy indicates that galaxies must accrete fresh gas in order to sustain star formation over their lifetime.

Galaxies can accrete gas from the environment in different ways depending on their mass. The most efficient accretion channel at early times is considered to be filamentary cold accretion from the inter galactic medium (IGM). Shock-heated gas surrounding galaxies (called hot corona) can also feed a galaxy if some physical mechanism is efficient in cooling this material (van de Voort et al., 2011). This channel, called hot accretion, becomes increasingly efficient with cosmic time. Worth mentioning are also minor mergers, which bring fresh gas onto galaxies. However, it has been shown that their influence to the total gas budget is negligibly small and insufficient to sustain star formation (Di Teodoro & Fraternali, 2014).

Star formation laws are empirical correlations linking the star formation rate (SFR) of a galaxy to its amount of gas. A commonly used law is that of Kennicutt (1998), which was first introduced by Schmidt (1959). The law is

$$\Sigma_{SFR} \propto \Sigma_{gas}^{N}, \tag{1.1}$$

where Σ_{SFR} and Σ_{gas} are the surface densities of the SFR and the gas distribution, respectively, and N describes the slope. Recent estimates of this parameter have confirmed that $N = 1.4 \pm 0.15$, as first estimated by Kennicutt (1998). However, several authors found that the validity of the Kennicutt law is limited to the high-density regions of galaxies, as this relation breaks down in the low-density environments Kennicutt (1989); de los Reyes & Kennicutt (2019); Bigiel (2010) A recent study by Bacchini et al. (2019a, 2020) has developed a new law, based on the volumetric rather than the surface densities. This volumetric star formation (VSF) law is

$$\rho_{SFR} \propto \rho_{gas}^{\alpha}, \tag{1.2}$$

where now ρ_{SFR} and ρ_{gas} are the volume densities of the SFR and the gas respectively, and the slope has been found to be $\alpha = 2.03^{+0.03}_{-0.03}$.

Crucially, the VSF law has a steeper slope that the Kennicutt law, and by using the volume densities no break is found at low densities. Such a break was interpreted as the projection effect of the flaring of the discs of galaxies. A comparison between the Kennicutt law and the VSF law is shown in Fig. 1.1 as taken from Bacchini et al. (2020). In the left panel, the surface densities of the SFR versus the total gas is plotted for a sample of spiral and dwarf galaxies, while the right panel shows the corresponding volume densities. Over the volume densities a fit of the VSF law is plotted.

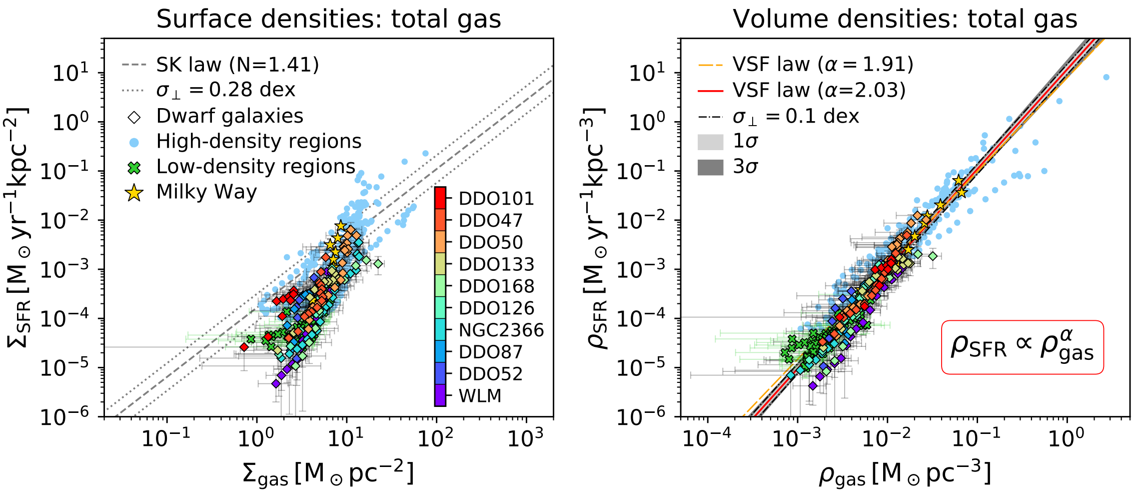


Figure 1.1: A comparison of the SFR plotted as a function of the total gas, in the left panel for the surface densities and in the right panel for the volume densities. The red line in the right panel is the best-fit relation to the volume densities and shows the VSF law. Image taken from Bacchini et al. (2020).

Fraternali & Tomassetti (2012) developed an evolutionary model for disc galaxies forming stars according to the Kennicutt law, with the aim of predicting the profile of the gas accretion rate across cosmic time. They applied this model to the Milky Way and 21 nearby galaxies finding that all galaxies have accreted a significant portion of their gas after $z = 1$. The main idea behind this work presented in this thesis is improving the disc evolution model by Fraternali & Tomassetti (2012) by implementing the VSF law instead of the Kennicutt law. We aim at understanding how the gas accretion rate as a function of time and position within the galactic disc changes when the star formation rate is changed. Given that the VSF law involves 3D quantities, this improvement allows us to predict the vertical profile of the gas accretion, in addition to the radial and temporal profiles. We apply this methodology to the Milky Way and compare our results with those obtained by Fraternali & Tomassetti (2012).

Chapter 2 describes the model, applying the same method as Fraternali & Tomassetti (2012), but now in volume densities rather than surface densities. The results are shown in Chapter 3, where we first compare the results obtained using the Kennicutt law (as in Fraternali & Tomassetti (2012)) with those based on the VSF law, and we show the gas accretion rate profile as a function of the galactocentric radius and the vertical heigth above the disc midplane, at different cosmic times. Conclusions and future prospects are described in Chapter 4.

Chapter 2

Description of the model

In this work, we make use of a simple model that describes the time evolution of the distributions of stars and gas in a disc galaxy. These kinds of models are usually constructed using the surface densities, but here we make a step forward by using the volume densities. These are not only more physically meaningful than surface densities, but also allow us to introduce a key novelty in our model, that is the use of the VSF law. This is a power-law relation linking the gas volume density in a galaxy with the SFR volume density and it was derived empirically for a sample of nearby disc galaxies (Bacchini et al., 2019a,b, 2020). Our main goal is to investigate how this improvement changes the predictions of evolutionary models of disc galaxies, with particular focus on the gas accretion rate that is required to sustain star formation across cosmic time.

To find an expression for the gas accretion rate, we express the evolution of the stellar volume density ($\rho_\star$) and the gas volume density (ρ_{gas}) as a function of lookback time (t) with the following equations

$$-\frac{\partial \rho_\star(R,z,t)}{\partial t} = +\rho_{SFR}(R,z,t) - \dot{\rho}_{fb}(R,z,t), \tag{2.1}$$

$$-\frac{\partial \rho_{gas}(R,z,t)}{\partial t} = -\rho_{SFR}(R,z,t) + \dot{\rho}_{fb}(R,z,t) + \dot{\rho}_{ext}(R,z,t), \tag{2.2}$$

where ρ_{SFR} is the star formation rate (SFR) volume density, $\dot{\rho}_{fb}$ is the gas volume density per unit time that is returned to the interstellar medium (ISM) by stellar evolution, and $\dot{\rho}_{ext}$ is the gas volume density that is accreted onto the galaxy from the environment or that is expelled from the galaxy. In practice, these equations are analogues to the more standard equations with surface densities that are usually employed in these evolution models (e.g. Fraternali & Tomassetti (2012)). Like the equations with surface densities, they describe the evolution of a disc composed of a series of rings that evolve independently, meaning that no radial flows of stars or gas are allowed. Radial motions in the stellar component can also be accounted for as stars migrate from their birth location, but we do not expect that our main results would change if stellar migration is included (Fraternali & Tomassetti, 2012).

We use the instantaneous recycling approximation (IRA), meaning that stellar feedback returns to the ISM a certain fraction ($\mathcal{R}$) of gas mass previously converted into stars instantaneously, so at the time stars are formed. This assumption significantly simplifies the equations and it is justified by the fact that most of the gas is returned by supernova explosions, which occur shortly after the birth of a stellar population. This enables us to write Eq. 2.1 and 2.2 as

$$-\frac{\partial \rho_\star(R,z,t)}{\partial t} = (1-\mathcal{R})\rho_{SFR}(R,z,t) \tag{2.3}$$

$$-\frac{\partial \rho_{gas}(R,z,t)}{\partial t} = -(1-\mathcal{R})\rho_{SFR}(R,z,t) + \dot{\rho}_{ext}(R,z,t). \tag{2.4}$$

We assume that $\mathcal{R} = 0.3$ at any time, consistent with (Fraternali & Tomassetti, 2012). Using the equation above, we obtain the relation for the volumetric gas accretion rate as

$$\dot{\rho}_{ext}(R,z,t) = (1-\mathcal{R})\rho_{SFR}(R,z,t) - \frac{\partial \rho_{gas}(R,z,t)}{\partial t}. \tag{2.5}$$

2.1 The star formation history of a disc galaxy

We model the evolution in time of the SFR following the same approach as Fraternali & Tomassetti (2012) and substituting, again, surface densities with volume densities. We assume that the SFR volume density as a function of R, z, and t is given by the SFR volume density distribution at the present day $\rho_{SFR}(R,z,0)$, multiplied by a dimensionless positive function, $f(R,t)$, describing the evolution of the star formation history (SFH) as a function of R:

$$\rho_{SFR}(R,z,t) = \rho_{SFR}(R,z,0)f(R,t). \tag{2.6}$$

In this first exploration we assume that the function $f(R,t)$ is independent of the vertical distribution, which implicitly implies that the vertical profile of the SFR does not change over time. The simplest choice for $f(R,t)$ is a linear profile (Fraternali & Tomassetti, 2012)

$$f(R,t) = 1 + [\gamma(R) - 1]\frac{t}{t_{form}}, \tag{2.7}$$

where t_{form} is the formation time of the galaxy and $\gamma(R) = f(R, t = t_{form})$.

The expression for $\gamma(R)$ can be obtained by integrating Eq. 2.3 and 2.6 over t, from the formation time to now, and by integrating over z. The equation is as follows (Fraternali & Tomassetti, 2012)

$$\gamma(R) = \frac{2\Sigma_\star(R,0)}{(1-\mathcal{R})t_{form}\Sigma_{\rm SFR}(R,0)} - 1, \tag{2.8}$$

where $\Sigma_\star(R,0)$ is the stellar surface density as a function of radius at $t=0$ and $\Sigma_{\rm SFR}(R,0)$ is the SFR surface density as a function of radius at $t=0$.

2.2 The star formation law

As anticipated, we assume that the conversion of gas into stars is regulated by the VSF law (Bacchini et al., 2019a), already briefly introduced in the introduction. The full law is given by

$$\rho_{SFR} = A\rho_{gas}^{\alpha}. \tag{2.9}$$

Here ρ_{SFR} is given in $M_{\odot}yr^{-1}kpc^{-3}$ and ρ_{gas} is given in $M_{\odot}pc^{-3}$, $A = 1.10$, and $\alpha = 2.03$ (Bacchini et al., 2020).

By inverting Eq. 2.9 to obtain ρ_{gas} and taking its time derivative, we obtain

$$\frac{\partial\rho_{gas}(R,z,t)}{\partial t} = \frac{\partial}{\partial t}\left[\left(\frac{\rho_{SFR}(R,z,t)}{A}\right)^{1/\alpha}\right] = \frac{1}{\alpha A^{1/\alpha}}\rho_{SFR}(R,z,t)^{\frac{1-\alpha}{\alpha}}\frac{\partial\rho_{SFR}(R,z,t)}{\partial t}. \tag{2.10}$$

Filling this into Eq. 2.5 along with Eq. 2.6, we obtain

$$\dot{\rho}_{ext}(R,z,t) = (1-\mathcal{R})\rho_{SFR}(R,z,0)f(R,t) - \frac{\rho_{SFR}(R,z,0)^{1/\alpha}}{\alpha A^{1/\alpha}}f(R,t)^{\frac{1-\alpha}{\alpha}}\frac{\partial}{\partial t}\left[f(R,t)\right], \tag{2.11}$$

which is analogous to Eq. 14 in Fraternali & Tomassetti (2012), but this time with volume densities.

The second term on the right hand side of the equation above contains the SFR volume density at $t = 0$ elevated to $1/\alpha$, which can be changed in terms of gas volume density using the VSF law Eq. 2.9, thus Eq. 2.11 can be rewritten as

$$\dot{\rho}_{ext}(R,z,t) = (1-\mathcal{R})\rho_{SFR}(R,z,0)f(R,t) - \frac{\rho_{gas}(R,z,0)}{\alpha}f(R,t)^{\frac{1-\alpha}{\alpha}}\frac{\partial}{\partial t}\left[f(R,t)\right]. \tag{2.12}$$

This equation is one of the main results of this work and represents the first (at least to our knowledge) expression for the gas accretion/expulsion rate onto/from a galaxy as a function of the position in the disc (R, z) and the lookback time t obtained with a simple analytical evolution model.

By integrating over z, Eq. 2.12 can be converted to surface densities

$$\dot{\Sigma}_{ext}(R,t) = (1-\mathcal{R})\Sigma_{SFR}(R,0)f(R,t) - \frac{\Sigma_{gas}(R,0)}{\alpha}f(R,t)^{\frac{1-\alpha}{\alpha}}\frac{\partial}{\partial t}\left[f(R,t)\right]. \tag{2.13}$$

This expression is nearly equivalent to the one obtained by Fraternali & Tomassetti (2012), but with the crucial difference given by the slope of the VSF law $\alpha \approx 2$, which is steeper than the slope of the Kennicutt law $N = 1.4$.

Chapter 3

Results

3.1 Comparison between the surface-based and the volume-based models

We now compare the results of our volume-based model with those obtained by Fraternali & Tomassetti (2012) using a surface-based approach. For this task, we focus on the Milky Way. We do not modify the adopted SFR surface density and SFH, and we also keep the same boundary conditions as Fraternali & Tomassetti (2012). Through the chapter we will assume $t_{form} = 10\ Gyr$.

3.1.1 Application to the Milky Way disc

Following Fraternali & Tomassetti (2012), we use the following expression to describe the SFR surface density profile at $t = 0$

$$\Sigma_{SFR}(R,0) = \Sigma_{SFR}(0,0)\left(1+\frac{R}{R_{SFR}}\right)^{\beta}\exp\left(-\frac{R}{R_{SFR}}\right), \tag{3.1}$$

where $\Sigma_{SFR}(0,0)$ is the normalisation of the present-day SFR surface density and R_{SFR} is the SFR scale length. As done by Fraternali & Tomassetti (2012), we impose $\Sigma_{SFR}(0,0) = 2.3\cdot 10^{-3}\ M_{\odot}kpc^{-2}yr^{-1}$ to match the present-day SFR of the Mily Way, which is assumed to be $SFR = 3\ M_{\odot}yr^{-1}$, and we set $R_{SFR} = 1.96\ kpc$ and the exponent $\beta = 3.10$. These parameters are obtained by fitting the profile to the observed SFR in the Mily Way, shown in Fig. 3.1.

The present-day gas distribution surface density is assumed to be well described by an equation analogous to that of the SFR surface density in Eq. 3.1. The equation then reads

$$\Sigma_{gas}(R,0) = \Sigma_{gas}(0,0)\left(1+\frac{R}{R_{gas}}\right)^{\zeta}\exp\left(-\frac{R}{R_{gas}}\right), \tag{3.2}$$

where $\Sigma_{gas}(0,0) = 2.43\ M_{\odot}pc^{-2}$, $\zeta = 3.07$, and $R_{gas} = 2.89\ kpc$. In this work the best-fit parameters were obtained by fitting the observed gas surface densities in the Milky Way as compiled in Bacchini et al. (2020). These surface densities include both atomic and molecular gas. The fit can be seen in Fig. 3.2.

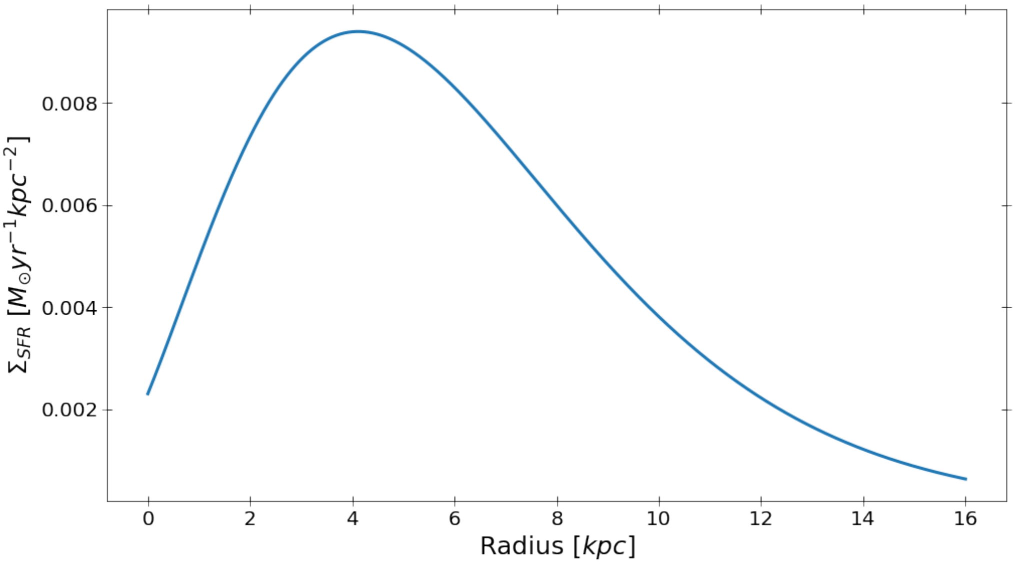


Figure 3.1: The present-day SFR surface density of the Milky Way as a function of radius. Model obtained by Fraternali & Tomassetti (2012) and normalized to a global star formation rate of 3 $M_\odot yr^{-1}$.

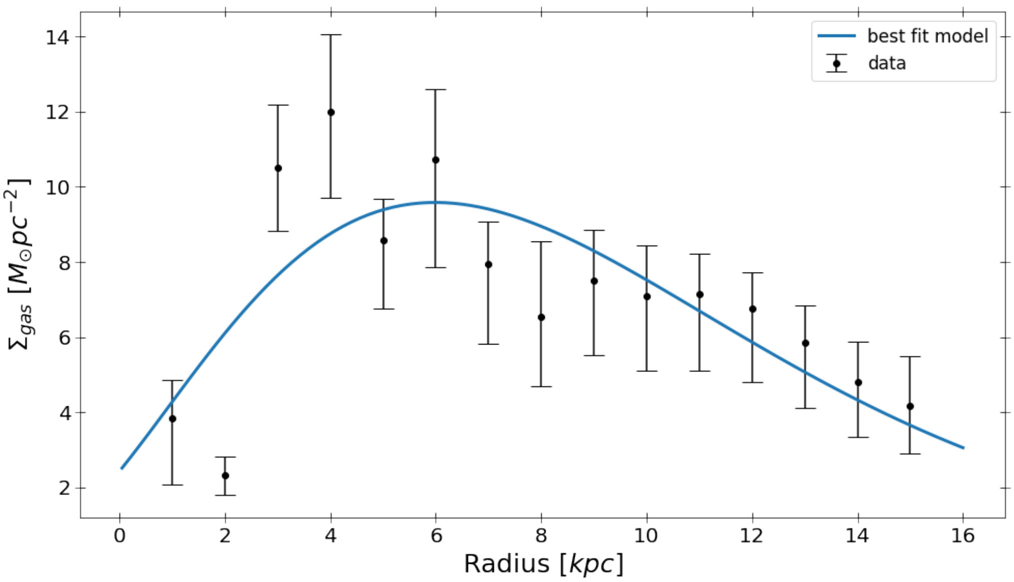


Figure 3.2: The present day gas distribution surface density of the Milky Way as a function of radius. The data (black points) come from the compilation of Bacchini et al. (2020), while the curve shows the best fit obtained with Eq. 3.2.

For the radial distribution of the present-day stellar mass surface density we assume a more standard exponential profile, such that

$$\Sigma_\star(R,0) = \Sigma_\star(0,0)\exp\left(-\frac{R}{R_\star}\right), \tag{3.3}$$

where $R_\star = 3.2\ kpc$ is the radial scale length and the normalisation $\Sigma_\star(0,0) = 6.5 \cdot 10^8\ M_\odot kpc^{-2}$ is obtained by imposing a total stellar mass of $M_{tot,\star} = 4{\cdot}10^{10}\ M_\odot$ (Fraternali & Tomassetti, 2012).

Having defined the surface densities of both the SFR and gas distributions in Eq. 3.1 and Eq. 3.3, we can use them to derive the gas accretion rate surface density using Eq. 2.13. This allows us to compare the gas accretion based on the Kennicutt law as done in Fraternali & Tomassetti (2012) to the gas accretion based on the VSF law. A depiction of the gas accretion over time at different radii is shown in Fig. 3.3.

From Fig. 3.3 it can be seen that the overall gas accretion is slightly higher for the volume-based model than that for the surface-based one. This is most noticeable at small radii ($0\ kpc < R < 6\ kpc$). We can now make a comparison between the two laws, the Kennicutt star formation law as in Eq. 1.1 and the VSF law as in Eq. 2.9, at different lookback times as can be seen in Fig. 3.4.

Again the gas accretion based on the VSF law is higher at the inner radii than the profile resulting from the surface-based model. This figure also shows that the gas accretion near the center of the galaxy is higher than in the outskirts of the galaxy nearly at every time except now.

3.2 Volumetric visualization of the gas accretion

In this section, we use Eq. 2.12 to calculate the gas accretion/outflow rate per unit volume. To this end we first update the SFR surface density of the Milky Way to a new determination. We us the SFR surface density profile derived by Green (2015) using supernova remnants as tracers of the distribution of recent star formation. The profile is as follows

$$\Sigma_{SFR}(R,t) = \Sigma_{SFR}(R,0)\left(\frac{R}{R_\odot}\right)^\mu \exp\left[-B\frac{(R-R_\odot)}{R_\odot}\right], \tag{3.4}$$

where the best fit parameters as found by Green (2015) and references within, are $\mu = 2.00 \pm 0.67$ and $B = 3.53 \pm 0.77$, and taking the Solar position $R_\odot = 8.5\ kpc$. $\Sigma_{SFR}(R,0)$ is found by normalizing the profile to a SFR of $3\ M_\odot yr^{-1}$, which results in $\Sigma_{SFR}(R,0) = 5.0 \cdot 10^{-3}\ M_\odot yr^{-1} kpc^{-2}$. The profile can be seen in Fig. 3.5. We note that, with respect to the profile shown in Fig. 3.1, the peak of the SFR surface density is shifted outwards, the radial outskirts are no longer forced to a SFR of zero, whereas the near galactic center region has a null SFR surface density in the Green (2015) profile.

We use the same stellar density profile as in Sect. 3.1.1 (Eq. 3.3).

To obtain the volume density profiles of the gas and the SFR in the midplane, we convert the surface densities using the equation

$$\rho(R,0) = \frac{\Sigma(R)}{\sqrt{2\pi}h(R)}, \tag{3.5}$$

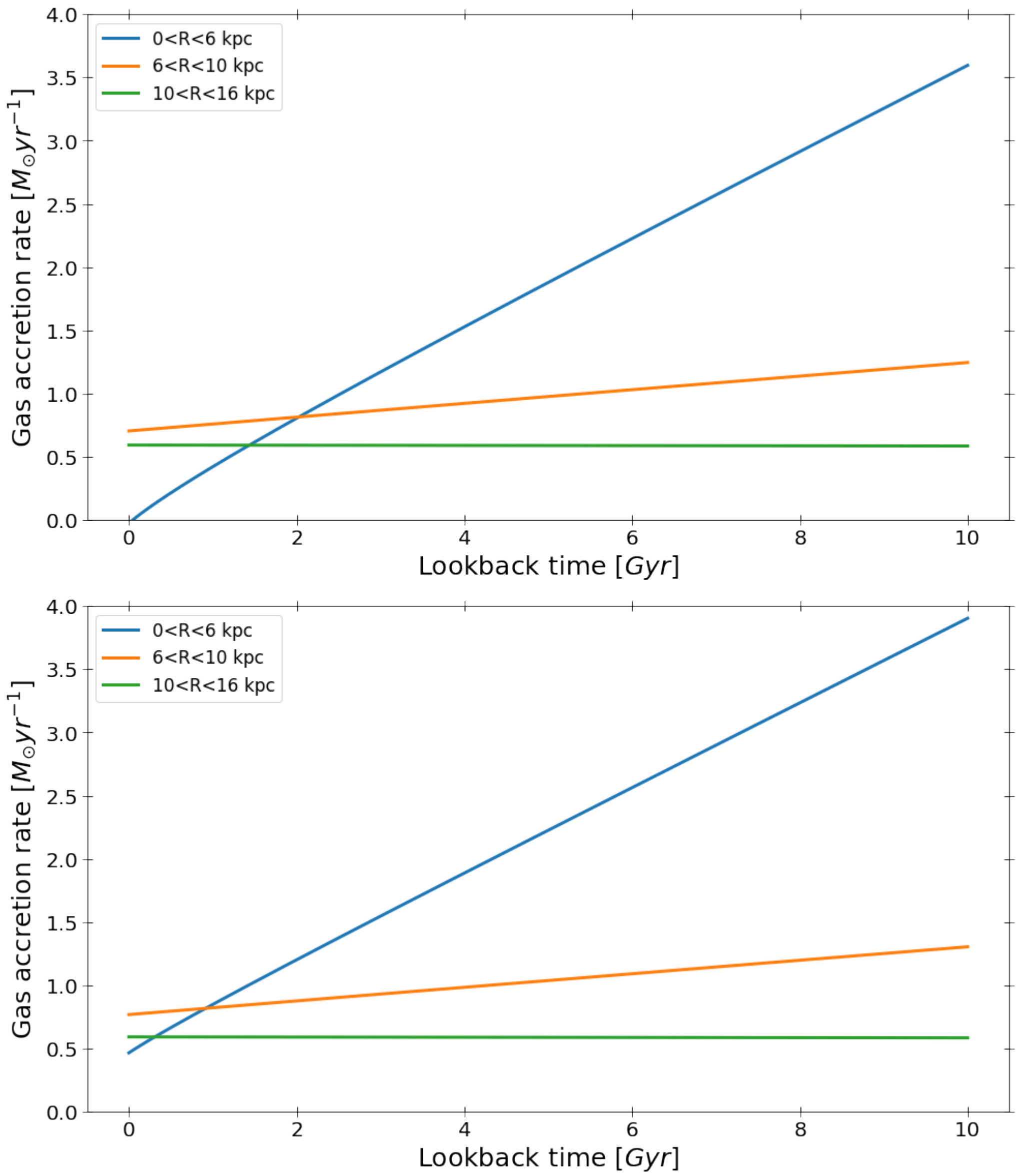


Figure 3.3: A comparison of the gas accretion rate as a function of lookback time in the Milky Way, obtained using the Kennicutt star formation law (top panel, as in Fraternali & Tomassetti (2012)) and the volumetric star formation law (bottom panel). Our accretion rate is calculated using Eq. 2.13. In both panels we show the total accretion rate as a function of lookback time in different portions of the galaxy disc.

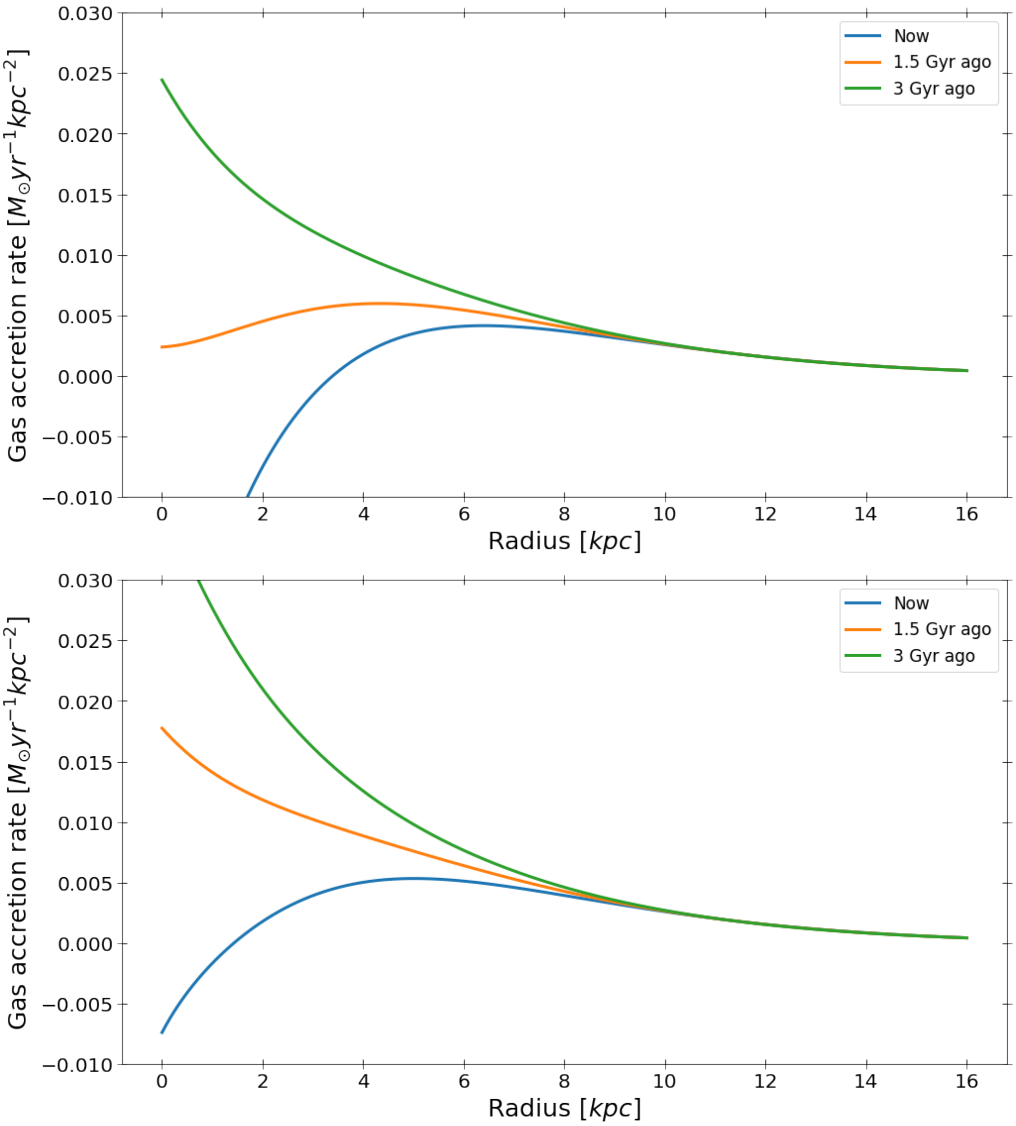


Figure 3.4: A comparison of the gas accretion rate over time between the Kennicutt star formation law (top panel, as in Fraternali & Tomassetti (2012)) and the volumetric star formation law (bottom panel). Our accretion rate is calculated using Eq. 2.13. In both panels we show the total accretion rate as a function of radius at different lookback times.

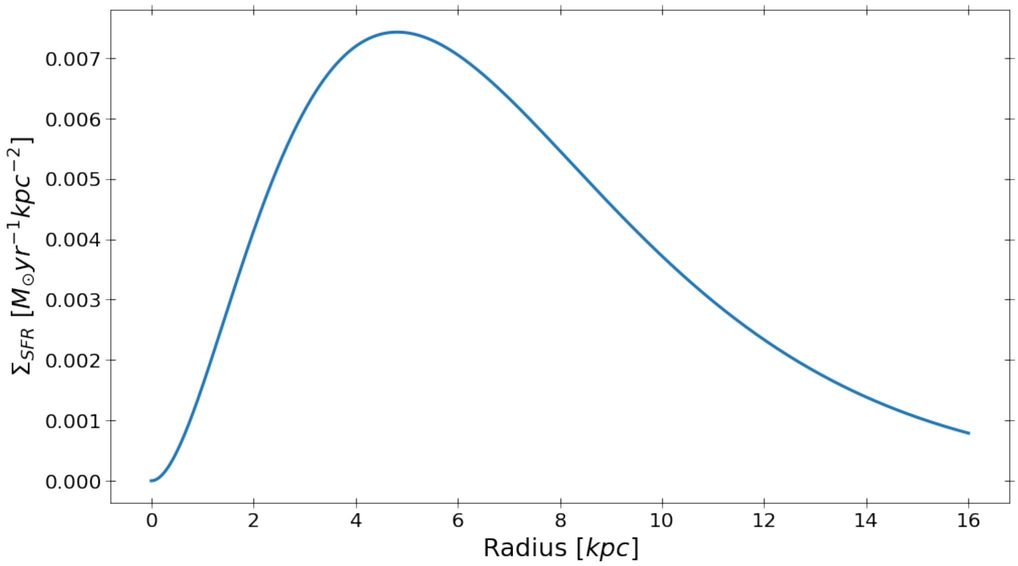


Figure 3.5: The star formation rate surface density of the Milky Way as a function of radius. Model obtained from Green (2015) and references within and normalized to a global star formation rate of 3 $M_\odot yr^{-1}$.

where $h(R)$ is the scaleheight. This assumes a Gaussian profile for the vertical distribution, which is expected for a gas disc in hydrostatic equilirium (see Bacchini et al. (2019a) for details). The volume density as a function of z can then be written as

$$\rho(R, z) = \rho(R, 0) \exp\left[-\frac{z^2}{2h^2(R)}\right], \tag{3.6}$$

with z the vertical distance from the midplane.

The scaleheights for both the SFR volume density and the stellar distribution in the Milky Way are taken from Bacchini et al. (2019a) and references within. Here however the value in the central region within a radius of 4 kpc is kept constant at the value found at 4 kpc, given the fact the scaleheight is poorly determined in those regions. The scaleheight profile is shown in Fig. 3.6.

Combining the scaleheight shown in Fig 3.6, the SFR density profile of Eq. 3.4, and Eq. 3.5 and 3.6, we can calculate the volumetric gas accretion rate as defined in Eq. 2.11. To be able to compare this new results with those seen before in Fig. 3.3 and Fig. 3.4, we first plot the gas accretion at the midplane ($z = 0$) at present time in Fig. 3.7.

The figure has the same general shape as the VSF law based model in the bottom panel of Fig. 3.4 at the time 'now'. The line in Fig. 3.4 does however become positive at $R = 1.5$ kpc, whereas the line in Fig. 3.7 becomes positive at $R = 2.8$ kpc. This seeming discrepancy can be explained by the fact that in the first case the plot shows the integration over z, meaning the total is expected to be a bit higher. Most importantly, it is the new Green (2015) SFR that is making a large difference in the central galaxy. There is a strong outflow of gas in the center, largely driven by the very low SFR visible in Fig. 3.5.

Now we can show two-dimensional plots based on Eq. 2.12 in Fig. 3.8, where six different moments in lookback time are shown.

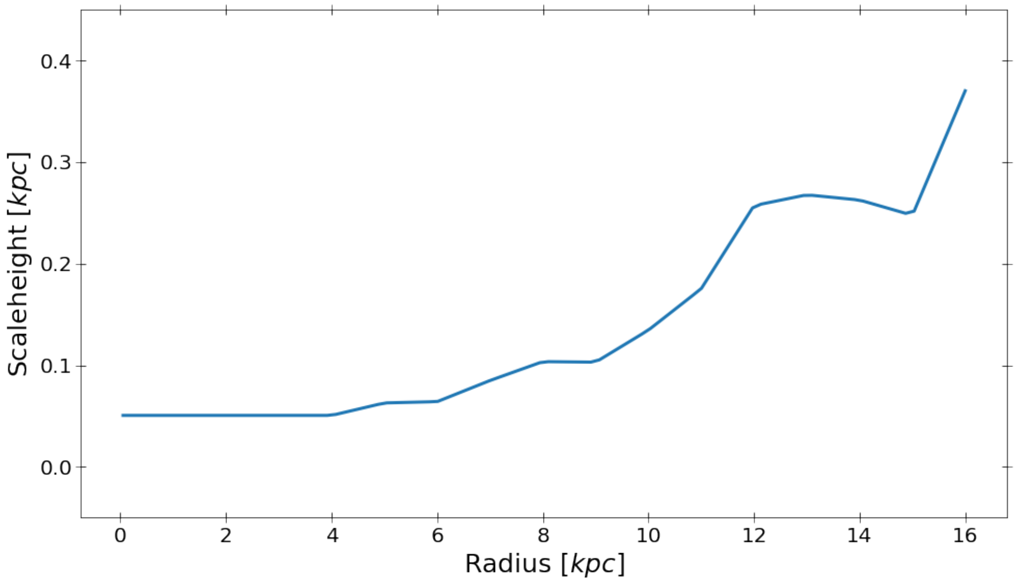


Figure 3.6: The scaleheight profile used for the star formation rate density profile and the stellar distribution in the Milky Way as obtained from Bacchini et al. (2019a) and references within. Due to the uncertainties in the determination of the scaleheight in the inner regions we chose to keep it constant for $R < 4$ kpc at the value found at $R = 4$ kpc.

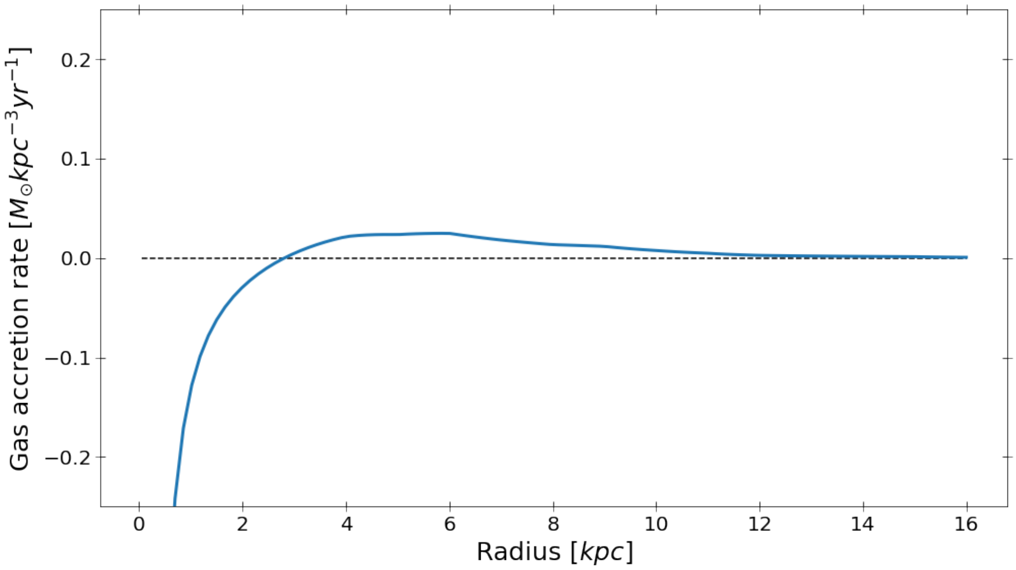
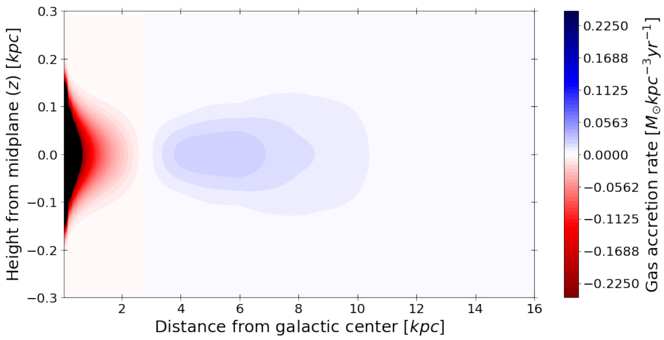
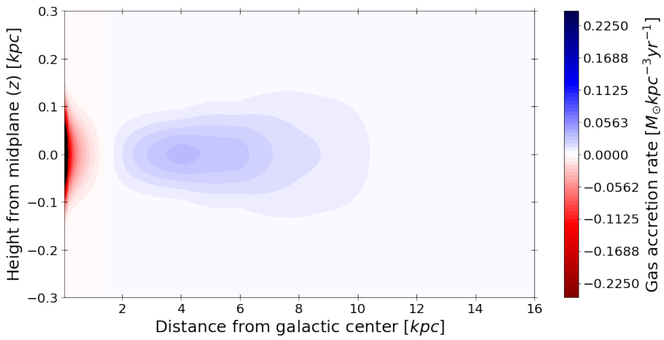


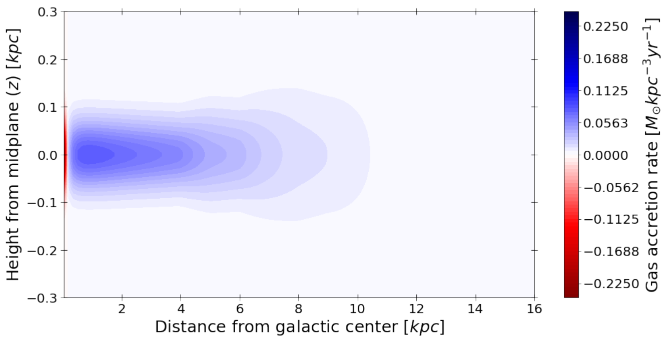
Figure 3.7: The gas accretion using the volumetric star formation law as defined in Eq. 2.11 in the midplane ($Z = 0$) at present time.



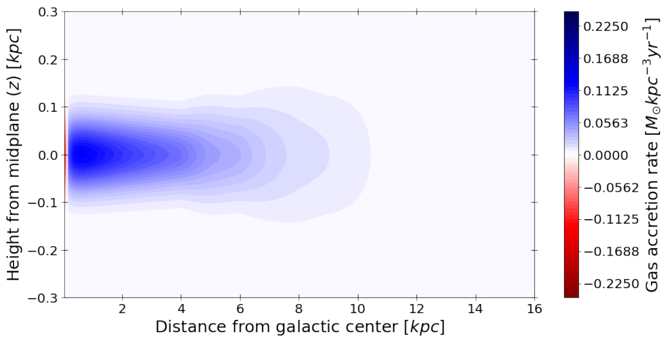
(a) Present



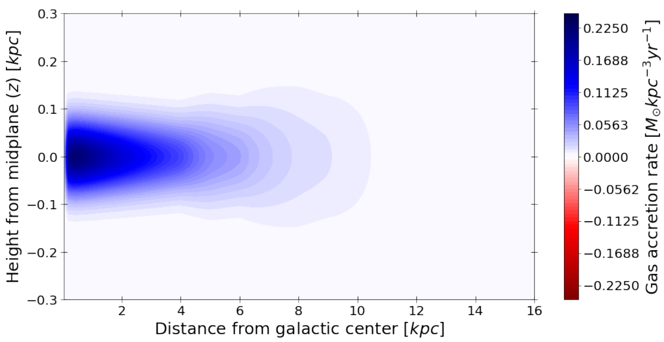
(b) Lookback time of 0.5 *Gyr*



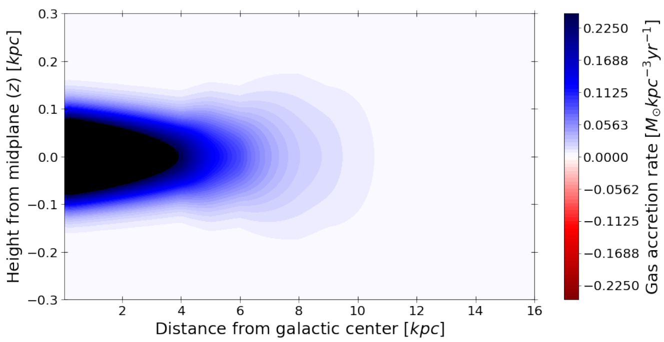
(c) Lookback time of 1.5 *Gyr*



(d) Lookback time of 2 *Gyr*



(e) Lookback time of 3 *Gyr*



(f) Lookback time of 10 *Gyr*

Figure 3.8: The gas accretion using the volumetric star formation law as in Eq. 2.12 at six different lookback times.

The shape of the gas accretion profile has developed a lot over time. Starting out mainly in the near galactic center (GC) region and showing signs of flaring in the outer regions. Starting 2 *Gyr* ago and settling around 1.5 *Gyr* ago the main gas accretion region has shifted more towards the region of about 5 *kpc* from the GC. The first signs of gas loss can also be seen at lookback time 1.5 and 2 *Gyr*, positioned near the GC and extending to a height of about 0.1 *kpc* from the midplane. The gas accretion region then shifts even more to the outskirts and starts to disappear around 0.5 *Gyr* ago. At present time gas accretion comes to a near halt.

Chapter 4

Conclusion remarks and future work

We have built a disc evolution model using a similar approach to Fraternali & Tomassetti (2012), but with the crucial modification of employing a volumetric star formation law instead of the surface-density based Kennicutt law. We applied our model to the Milky Way.

The gas accretion profiles predicted by the models based on the Kennicutt law and the VSF law are similar (see Fig. 3.3 and 3.4). Overall the gas accretion is a slightly higher, in particular in the inner galaxy. There is general decrease of the accretion rate over time.

We built two-dimensional maps (Fig. 3.8) using the new Green (2015) determination of the SFR surface density. Such maps confirm that the gas accretion rate decreases over time. In the disc outskirts, we also observe a flaring (increase of the scale height) of the profile of the gas accretion rate. With decreasing lookback time, the peak of the gas accretion rate shifts towards larger distances from the galaxy center, reaching values for the present-day Milky Way lower than those obtained by Fraternali & Tomassetti (2012).

The measurements of the gas density and SFR in the central part of the galaxy are very uncertain, mainly due to dust obscuration and the influence of the stellar bar. Therefore, our results should be taken with caution in the regions within ≈ 3 *kpc*.

A future improvement of the model would consist of substituting the linear function describing the SFH (Eq. 2.7) with an exponential function, as this would describe more accurately recent estimates of the cosmic SFH.

Our present model assumes no flows of gas and stars both in the z and R directions. An improvement for future research would be to include gas flows and/or stellar migration using known predictions from other models or finding further constraints and boundary conditions.

Chapter 5

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