Implementing Dust Shielding as a Criteria for Star Formation

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Abstract

Star formation is observed to be strongly correlated to dense regions of molecular gas. Although the exact nature of the link between star formation and molecular hydrogen is still unclear, some have suggested that shielding of dense gas by dust grains is the key factor enabling the presence of both. We present a subgrid model for use in galaxy formation simulations in which star formation is linked explicitly to local dust shielding. We developed and tested our shielding and star formation models using smoothed particle hydrodynamic simulations of solar and subsolar metallicity isolated Milky Way–mass disk galaxies. We compared our dust-shielding-based star formation model to two other star formation recipes that used gas temperature and H2 fraction as star formation criteria. We further followed the evolution of a dwarf galaxy within a cosmological context using both the shielding and H2-based star formation models. We find that the shielding-based model allows for star formation at higher temperatures and lower densities than a model in which star formation is tied directly to H2 abundance, as requiring H2 formation leads the gas to undergo additional gravitational collapse before star formation. However, the resulting galaxies are very similar for both the shielding and H2-based star formation models, and both models reproduce the resolved Kennicutt–Schmidt law. Therefore, both star formation models appear viable in the context of galaxy formation simulations.

Key words: galaxies: dwarf – galaxies: evolution – hydrodynamics – methods: numerical – stars: formation

1. Introduction

Processes determining star formation drive the evolution of the stellar content in galaxies. Mimicking these processes in galaxy evolution simulations is critical to correctly model the stellar mass and distribution. However, because star formation happens on scales too small to be resolved in simulations of galaxy evolution, stochastic subgrid models must be used to model it instead. It is therefore imperative to determine which models best mimic the actual process of star formation and produce star formation rates and locations that agree with observations from real galaxies. Additionally, comparing the effects of different star formation subgrid models can reveal the primary drivers of star formation on 100 pc scales.

Considerable observational evidence links the formation of stars to the surface density of gas in the star-forming region. Schmidt (1959) suggested that this link takes the form of

$$\rho_{\text{SFR}} \propto \rho_{\text{gas}}^N$$

and suggested that $N \approx 2$. Kennicutt (1998) refined this relationship through observations of spiral and starburst galaxies, yielding the power law $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$. However, more recent observational evidence suggests that star formation is linked specifically to the density of molecular gas. Wong & Blitz (2002) found that star formation rate surface density is correlated more closely with the surface density of molecular hydrogen than to the total gas surface density, a result that has been replicated by others (Boissier et al. 2003; Heyer et al. 2004). Similarly, Kennicutt et al. (2007) observed a strong correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H2}}$, but no significant correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H1}}$. Bigiel et al. (2008) also showed that the relationship between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$ varied dramatically, while $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H2}}$ were consistently related by a Schmidt-type power law with $N = 1.0 \pm 0.2$. Various other studies have also found a strong and approximately linear relationship between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H2}}$ (Bigiel et al. 2011; Schruba et al. 2011; Leroy et al. 2013), confirming the link between star formation and H2, rather than total gas.

One possible explanation for this link is that molecular hydrogen is required for star formation to occur. For example, Krumholz et al. (2009) demonstrated that the observed relationship between galaxies’ star formation rate and their atomic and molecular gas content can be explained by a model in which stars formed only out of molecular gas, at a rate given by 1% of the mass per freefall time. Moreover, simulations in which star formation is explicitly linked to local H2 abundance have produced galaxies consistent with the observed Kennicutt–Schmidt and Tully–Fisher relations (Gnedin et al. 2009; Christensen et al. 2012; Kuhlen et al. 2012), as well as the observed relations between ISM pressure and molecular fraction (Robertson & Kravtsov 2008).

However, although H2 traces star formation, it need not be a direct prerequisite for star formation to occur, as cooling in dense clouds of gas occurs primarily by CII or CO lines. Indeed, by modeling star formation within a dense cloud of gas, Glover & Clark (2012) found that the presence of molecules in a gas cloud does not determine the cloud’s ability to form stars. Indeed, they suggested that as long as a cloud of gas is dense and gravitationally unstable, cooling by H2 is not necessary for star formation to occur. Therefore, it is probable that molecular hydrogen is not required for star formation but instead simply correlated with it. For example, Mac Low & Glover (2012) have suggested that star formation and the presence of molecular gas both occur due to gravitational instability rather than being causally linked. Assuming such a situation, Krumholz (2012) demonstrated that in low-metallicity environments, below a few percent of solar metallicity, stars should
be able to form without the presence of molecular hydrogen. Since the freefall time of the gas will be longer than the thermal equilibrium timescale but shorter than the chemical equilibrium timescale, gas collapse will occur before the formation of H$_2$. This theory is supported by the high atomic, low molecular content of gamma-ray burst host galaxies, which may arise when low-metallicity gas accretes onto a galaxy, then cools and collapses into stars before H$_2$ can be formed (Michałowski et al. 2015).

The possibility that molecular hydrogen is not necessary for star formation has implications both for our understanding of galaxy formation and for our ability to accurately model star formation in low-density and low-metallicity environments. In particular, the low metallicity of the high-redshift universe makes it an extreme environment for understanding star formation. Even after enrichment from population III stars, requiring H$_2$ for star formation could have profound effects on the high-$z$ luminosity function, especially at the low-mass end (Kuhlen et al. 2012). Low-H$_2$ star-forming environments also exist at low redshifts. For example, although the outer disks of spiral galaxies lack significant amounts of molecular gas, star formation can still occur, albeit inefficiently (Ferguson et al. 1998; Thilker et al. 2005; Bigiel et al. 2010). The same is true for the low-surface density, low-metallicity environments of dwarf galaxies (e.g., van Zee et al. 1997; Leroy et al. 2006; Melena et al. 2009; Roychowdhury et al. 2009). In order to accurately model these environments, we must understand the process of star formation in environments with low amounts of H$_2$.

If molecular hydrogen is not a prerequisite for star formation, other factors must be considered. One potential explanation is that shielding by dust leads to both the formation of molecular hydrogen and the formation of cold gas necessary for gravitational collapse and star formation. Schaye (2004) argued that the transition of gas to the cold phase at high column densities both allows star formation to occur and coincides with an increase in the molecular fraction, as H$_2$ forms more readily in dense gas and contributes to further cooling. Using detailed simulations of chemical evolution within collapsing gas clouds, Glover & Clark (2012) found that the column density of gas clouds and the associated dust shielding are the determining factors for both the creation of molecules and star formation. Dust shielding both reduces photodissociation of H$_2$ by Lyman–Werner (LW) radiation and blocks photoheating by the Interstellar Radiation Field (ISRF); this allows cold, dense gas to form in the same regions where molecular hydrogen is able to form and remain. They argue that shielding of the ISRF, not the presence of H$_2$ or CO, is the most important factor enabling star formation in gas clouds, a conclusion that has also been reached by others (e.g., Krumholz et al. 2011; Clark & Glover 2014).

The evidence for a strong connection between dust shielding and star formation suggests that the accuracy and realism of numerical simulations may be increased by making star formation explicitly dependent on dust shielding. Such a model might allow for star formation to occur in areas or on timescales that a H$_2$-based recipe would preclude. Here we implement a dust-shielding-based star formation recipe and compare ISM and star formation properties of the resulting simulated galaxies to those produced using a temperature ceiling model and a H$_2$-based model. We further analyze the effects of shielding versus H$_2$-based star formation on a cosmological simulation of a dwarf galaxy by comparing disk size, star formation history, and the location of star formation. The comparison of shielding to other criteria enables a greater understanding of the link between dust shielding and star formation, and therefore how to more accurately model galaxy formation.

2. Methodology

We implement a novel method for dust-shielding-based star formation for use within smoothed particle hydrodynamic galaxy formation simulations, including incorporating an updated method for calculating shielding. Below, we describe the isolated disk galaxy and cosmological galaxy formation simulations used to test our star formation and shielding models (Section 2.1). We then introduce the smoothed particle hydrodynamic code used (Section 2.2) and describe our implementation of shielding (Section 2.3) and star formation (Section 2.4).

2.1. Initial Conditions

To test our shielding and star formation models, we used simulations of a $1.4 \times 10^{12} M_\odot$ isolated Milky Way–like disk galaxy within a Navarro et al. (1997) dark-matter halo. Following the work of Kaufmann et al. (2007) and Stinson et al. (2007), disks were formed by allowing a cloud of virialized gas to collapse within a virialized dark-matter halo with a concentration of $c = 8$, where $c = R_{\text{vir}}/R_\text{s}$ and $R_\text{s}$ is the scale radius of the Navarro–Frenk–White profile. The initial halo had a gas fraction of 10%, and the gas particles were given an initially uniform circular velocity such that the dimensionless spin parameter $\lambda = (J_{\text{gas}}/|E|^2)/(GM^2/2) = 0.039$, where $J_{\text{gas}}$ is the average specific angular velocity of the gas, and $E$ and $M$ are the total energy and mass of the halo. The initial masses of the star, gas, and dark-matter particles were $3.4 \times 10^4 M_\odot$, $1.4 \times 10^5 M_\odot$, and $1.3 \times 10^6 M_\odot$, respectively. The gravitational softening length was 206 pc and the smoothing lengths had a minimum value of 0.1 times the softening length. After 1 Gyr, following the formation of a stable disk, we scaled the gas metallicities to create one simulation with average ISM metallicity of 1.0 Z$_\odot$ and one with 0.1 Z$_\odot$. These two isolated disk galaxies formed the initial conditions for testing our star formation and shielding models. We then enabled H$_2$ physics along with our various shielding and star formation models described below, and integrated the simulations for an additional 1.0 Gyr.

We also tested the effects of our shielding implementation using a zoom-in (Katz & White 1993) cosmological simulation of a dwarf galaxy, $M_{\text{vir}} = 4 \times 10^9 M_\odot$. A dwarf galaxy was chosen to highlight the impact of our model in a low-metallicity environment. The initial conditions consisted of a 25 Mpc box selected to surround a halo chosen from a low-resolution, dark-matter-only simulation. The CMBFAST code was used to calculate the initial power spectrum used for the linear density field. We assumed a ΛCDM cosmology with values from the Wilkinson Microwave Anisotropy probe (Spergel et al. 2003). The masses of the star, gas, and dark-matter particles were 1000, 3000, and 16,000 solar masses respectively, and the softening lengths were 87 pc.

The initial conditions for this simulation were first used in Governato et al. (2010) and produced a bulgeless dwarf galaxy. Christensen et al. (2012) simulated the same galaxy with the
addition of metal line cooling and H$_2$-based star formation. Compared to a simulation with metal-line cooling and density-based star formation, they found that the addition of H$_2$-based star formation produced a clumpier ISM and on-going star formation at $z = 0$.

2.2. General Description of Code

The simulations were performed using the galaxy formation code CHANGA, an N-body smoothed particle hydrodynamics (SPH) code (N-Body Shop 2011; Menon et al. 2014). CHANGA is a highly scalable successor to GASOLINE (Wadsley et al. 2004), itself an extension of the parallel, gravity tree code PKDGRAV (Stadel & Gerhard 2002). CHANGA employs a modern implementation of the SPH kernel that uses a geometric mean density in the force expression (Ritchie & Thomas 2000; Menon et al. 2014; Wadsley et al. 2017), thus eliminating artificial gas surface densities.

CHANGA incorporates a suite of physical modules for thermodynamics, star formation, and stellar feedback, as described below. Nonequilibrium ion abundances, including H$_2$, are calculated by integrating over the H and He chemical networks. Heating and photoionization are determined using a cosmic ultraviolet background (Haardt & Madau 2005).\(^6\) Cooling is calculated via collisional ionization (Abel et al. 1997), radiative recombination (Black & Hasd., 1981; Verner & Ferland 1996), photoionization, bremsstrahlung, and H, He, and metal line cooling (Cen & Renyu 1992; Shen et al. 2010b). To calculate the nonequilibrium abundance of molecular hydrogen, we adopt the model developed by Christensen et al. (2012). Local, nonequilibrium H$_2$ abundances are determined by the rates of dust grain H$_2$ formation, gas-phase H$_2$ formation, collisional dissociation, and photodissociation by LW radiation from nearby stellar particles. H I and H$_2$ are both shielded by dust and H$_2$ is additionally self-shielded. The LW flux used for calculating the rate of H$_2$ photodissociation and heating for a given gas particle is approximated based on the cosmic ultraviolet background and the average LW flux from nearby star particles. In calculating the stellar LW radiation, the particle gravity tree is used to select proximate gas particles, as described in Christensen et al. (2012). This method avoids a full radiative-transfer calculation while still approximating the spatial and temporal variation in the LW flux. When determining the rates of H$_2$ photodissociation and heating, we further include a subgrid model for dust and self-shielding. This same dust shielding model is also used in determining the rates of photoionization and heating of H I by the cosmic ultraviolet background. The subgrid shielding models and the different techniques we explored to estimate column length are described in detail in Section 2.3. Star formation rates are determined stochastically based on local gas properties, described for each model in Section 2.4.

The simulations use the blastwave supernova (SN) feedback model described in Stinson et al. (2006), in which each SN releases $10^{51}$ ergs of energy into the surrounding gas. For SNe II, radiative cooling is disabled within the blastwave radius during the theoretical lifetime of the momentum-conserving phase of the SN remnant. This subgrid recipe prevents artificial cooling and allows affected gas to naturally rise from the disk without the use of a momentum kick. SNe I and II also inject metals into the ISM. These simulations assume a Kroupa (2001) initial mass function, SNe rates from Raiteri & Villata (1996), and metal yields from Woosley & Weaver (1995) and Thielemann & Nomoto (1986). Metals are also returned to the ISM by stellar winds using mass-loss rates from Weidemann (1987), and they are dispersed using a shear-dependent subgrid turbulent mixing model (Shen et al. 2010a) with a metal diffusion coefficient of 0.03.

2.3. Shielding Recipes

Shielding is responsible for the preservation of H$_2$ in dense gas as both dust and self-shielding protect the gas from photodissociation. We examine the role that dust shielding may play in promoting star formation by preventing photoheating. As part of these efforts, we improve our shielding models through the implementation of a new model for calculating column length based on Safranek-Shrader et al. (2017).

Shielding has significant effects on scales below the resolution limit of our simulations. We account for these effects with a local, subgrid approximation of shielding, following the work of Draine & Bertoldi (1996), Glover & Mac Low (2007), and Gnedin et al. (2009). The dust shielding $S_d$ and self-shielding $S_{H_2}$ functions were implemented as in Christensen et al. (2012): we calculated the dust shielding as

$$S_d = e^{-\sigma_d Z J_{\text{eff}}}$$

(1)

where $N_{H_1}$ and $N_{H_2}$ are the column densities of H I and H$_2$ respectively, $Z$ is the metallicity, and $\sigma_d$ is a parameter representing the effective attenuation cross section, tuned to be $2 \times 10^{-21}$ cm$^2$. The H$_2$ self-shielding is calculated as

$$S_{H_2} = \frac{1 - \omega_{H_2}}{(1 + x^2)} + \frac{\omega_{H_2}}{(1 + x^{1/2})} e^{-0.00085(1 + x)^{1/2}},$$

(2)

where $\omega_{H_2}$ is an adjustable parameter tuned to be 0.2 and $x = N_{H_2}/(5 \times 10^{14})$ cm$^{-2}$.

The column densities are the product of the column length associated with each gas particle and the number densities of H I and H$_2$. The molecular hydrogen recipe introduced in Christensen et al. (2012) assumed the column length to be equal to the particle smoothing length, $h$, a recipe that we will refer to as $S_{\text{smooth}}$. However, this recipe has the potential to be susceptible to resolution effects. More recently, Safranek-Shrader et al. (2017) evaluated several common approximations for shielding length—including the Sobolev approximation, the Jeans length, a length based on the local density and its gradient, a power-law approximation, and a single-cell approximation—and compared them to a detailed ray-tracing solution to the radiative transfer problem. They found that a temperature-capped Jeans length performed well at matching the effective visual extinction and performed better than other local models at calculating mass-weighted abundances of H$_2$ and CO.

In the $S$ model, we consider the shielding length to be equal to the particle Jeans length using the empirically chosen temperature ceiling of 40 K from Safranek-Shrader et al. (2017):

$$L_{\text{shield}} = \sqrt{\frac{15 k_B T}{4 \pi G m_H \rho}},$$

(3)

where $T$ is the minimum of the particle’s temperature and 40 K, $m_H$ is the mass of atomic hydrogen, and $\rho$ is the gas density.

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\(^6\) Haardt & Madau (2005) refers to an unpublished updated version of Haardt & Madau (1996), specified in CLOUDY (Ferland et al. 1998) as “table HM05.”
We also investigated the use of a Jeans length approximation for shielding length without a temperature ceiling (the $S_{\text{Jeans}}$ model).

In order to assess the differences among our shielding recipes, we examined the resulting column lengths of gas particles in isolated disk galaxies generated using the $S_{\text{smooth}}$, $S$, and $S_{\text{Jeans}}$ models. We found that the $S_{\text{Jeans}}$ model resulted in significantly longer column lengths than the $S_{\text{smooth}}$ or $S$ models (Figure 1). In that model, high-temperature, low-density gas is modeled as having a long column length, increasing the column densities and dust shielding beyond what would be expected in reality. This supports the findings of Safranek-Shrader et al. (2017), who concluded that H$_2$ and CO abundances were significantly overpredicted by a Jeans length shielding model without a temperature cap. The temperature-capped Jeans length, however, led to column lengths similar to the smoothing lengths in the $S_{\text{smooth}}$ simulation. The extent of the impact of the different column length recipes is further analyzed in Figure 2, which compares column lengths as a function of density. Although the column lengths in the $S_{\text{Jeans}}$ simulation are significantly longer on average than the column lengths in the other two shielding simulations, the effect is less significant when looking only at gas particles eligible for star formation, indicated by darker shades in the diagram. The $S$ model creates the shortest column lengths at high (i.e., potentially star-forming) densities. We also note that because almost all gas has temperatures greater than 40 K, the $S$ column lengths are generally simply proportional to $\rho^{1/2}$. Additionally, for gas particles with equal masses and $T > 40$ K, the column lengths for $S$ and $S_{\text{smooth}}$ will be correlated with each other.

To further test our shielding model, we examined the H I+H$_2$ surface densities at which hydrogen transitioned from atomic to molecular for simulations using the $S$ model at subsolar metallicity ($S_{\text{LM}}$) and with a factor of 10 lower mass resolution ($S_{L\text{R}}$) (Figure 3). Surface densities were calculated per-particle as $\Sigma_{\text{HI+H}_2} = \rho(N_{\text{HI}} + 2N_{\text{H}_2})L_{\text{shield}}$. As metallicity decreased, the transition moved to slightly higher column densities because dust shielding and the rate of H$_2$ formation decreased. The transition occurs at the same density for the high and low resolution simulations, indicating that the transition is independent of the number of particles over this range of resolutions. Conditions differed by a factor of 10, the shift in the transition was roughly a factor of 2. The reduced shift was because of a combination of factors. First, self-shielding, which is not metallicity-dependent, is significant at high densities, enabling the transition from H I to H$_2$ to occur at lower surface densities than dust shielding alone would predict. Second, although the average metallicity was initially $z = 0.1Z_{\odot}$ for the low-metallicity simulation, we found that the difference in
The probability of a sufficient cold and dense gas particle spawning a star particle is adopted from Stinson et al. (2006):

\[ p = \frac{m_{\text{gas}}}{m_{\text{star}}} (1 - e^{-c^* \Delta t / \nu_{\text{smooth}}}), \]  

where \( m_{\text{gas}} \) and \( m_{\text{star}} \) are the masses of the gas particle and the potential star particle respectively, \( \nu_{\text{form}} \) is the local dynamical time, and \( c^* \) is a star-forming efficiency factor, whose functionality depends on the model, as described below.

In the H2 recipe, star-forming efficiency was linked to the local abundance of molecular hydrogen:

\[ c^* = c_0^* X_{\text{H}_2}, \]  

where \( X_{\text{H}_2} \) is the number fraction of \( \text{H}_2 \), and \( c_0^* \) is an adjustable parameter tuned to 0.1 for the isolated galaxies and 0.01 for the cosmological simulations, values chosen to produce reasonable Kennicutt–Schmidt relations for the H2 model. In the shielding recipes, we modified the efficiency factor to be dependent on dust shielding:

\[ c^* = c_0^* (1 - S_d), \]  

where \( S_d \), as defined in Equation (1), is the fractional reduction in the intensity (so \( S_d = 1 \) corresponds to no shielding by dust). We used the same value of \( c_0^* \) as in the H2 recipe. In the temperature-based recipe (TC), only those particles passing a more stringent temperature cut were allowed to form stars, and we used a constant value of \( c^* = c_0^* \). We only tested the TC recipe on the isolated galaxies and used the same value of \( c_0^* = 0.1 \) as in the H2 and S cases for those galaxies.

All models required gas particles to meet temperature and density criteria (\( \rho \geq \rho_{\text{min}} \) and \( T \leq T_{\text{max}} \)) to be eligible for star formation. The same density threshold was used across all models: \( \rho_{\text{min}} \geq 0.1 \text{ amu cm}^{-3} \), a value chosen to be low enough to have no significant effect on star formation. For H2 and shielding-based star formation models, \( T_{\text{max}} \) was set to 15,000 K, a temperature cut high enough to have no significant effect on star formation. For TC, \( T_{\text{max}} \) was lowered to 1000 K, a temperature chosen to be similar to the upper temperature at which particles in the simulation contained significant amounts of \( \text{H}_2 \). This temperature ceiling must be higher than the observed temperature of molecular clouds to reflect the limited resolution of the simulations.

In order to test the accuracy of our models, we compared the \( \text{H}_1+\text{H}_2 \) surface densities at which hydrogen transitioned from atomic to molecular for isolated disk simulations at solar metallicity. The surface densities are plotted in Figure 4 and compared to Milky Way observational data from Gillmon et al. (2006) and Wolfire et al. (2008) determined from absorption spectroscopy. In addition to showing the results of the three different star formation models, we also include shielding-based star formation using the previously discussed \( S_{\text{smooth}} \) and \( S_{\text{Jeans}} \) shielding models. In all other simulations, shielding was calculated using the S model.

In order to ensure an accurate comparison to observations, the surface densities and \( \text{H}_2 \) fractions were calculated from mock observations generated by post-processing the galaxy to create velocity cubes of \( \text{H}_1 \) and \( \text{H}_2 \). The cubes were produced by using the smoothing kernel to spatially distribute the gas particles, and then calculating the expected amount of 21-cm emissions and binning it in \( x, y, \) and velocity space. Data were generated in 128 velocity channels with 1.3 km s\(^{-1}\) bins and a 5 pc pixel size.

All models were able to successfully reproduce the observed transition from atomic to molecular hydrogen, indicating that all shielding models produced reasonable behavior. The different star formation criteria allowed for different amounts of \( \text{H}_2 \), as will be discussed further in Section 3. The H2 and S models produced the greatest amounts of \( \text{H}_2 \)-rich gas, as in the other models, gas particles frequently formed stars before a large amount of \( \text{H}_2 \) could accumulate.

Linking star formation to molecular or shielded gas relegates star formation to generally dense and cold gas for which the Jeans mass may no longer be resolved. Robertson & Kravtsov (2008), therefore, advocated the adoption of a pressure floor to prevent numerical Jeans fragmentation of dense, cold gas. However, the use of a pressure floor has also been rejected as artificial or unnecessary. For example, Christensen et al. (2012) found that the addition of a Jeans pressure floor did not significantly affect the number or distribution of stars formed for simulations of this resolution, as gas particles for which the

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### Table 1

| Model | SF Recipe | \( L \_s \) | \( T_{\text{max}} \) (K) | \( c^* \)
|-------|-----------|----------------|-----------------|----------------|
| TC    | Temperature cap | \( \lambda_f \) (\( T \leq 40 \)) | 1000 | \( c_0^* \)
| H2    | H2 fraction | \( \lambda_f \) (\( T \leq 40 \)) | 15000 | \( c_0^* X_{\text{H}_2} \)
| S     | Shielding fraction | \( \lambda_f \) (\( T \leq 40 \)) | 15000 | \( c_0^* (1 - S_d) \)

*Note. \( L \_s \) is the shielding length used to calculate \( \text{H}_2 \) abundance and (if applicable) star formation. \( \lambda_f \) is the jeans length of a gas particle, while \( h \) is the smoothing length. \( T_{\text{max}} \) is the maximum temperature at which gas particles can form stars, \( c^* \) is the star formation efficiency factor. For all models, the minimum density at which stars can form is \( \rho_{\text{min}} = 0.1 \text{ amu cm}^{-3} \).*
Jeans mass and length are unresolved necessarily meet the star formation criteria. Hopkins et al. (2018) similarly found artificial pressure floors in SPH simulations to be unnecessary and unphysical. We tested the impact of adding a Jeans pressure floor to the S shielding model and found that, due to the high resolution of the simulation, it did not create any significant differences in star formation history, gas density, or gas distribution. The average density at which gas formed into stars was not affected by the presence of a Jeans pressure floor, as shown in Figure 5. All models discussed in this paper, therefore, do not have an artificial pressure floor.

3. Results

We analyzed the effects of including shielding-based star formation and compared it to the more traditional star formation recipes of a temperature-capped model and a H$_2$ abundance-based model, as shown in Section 3.1. We used solar and subsolar metallicity isolated disk simulations to examine the properties of the star-forming gas for each of the three models. By examining the temperatures and densities at

Figure 4. Transition from atomic to molecular hydrogen as a function of surface density for isolated, Milky Way–like simulations with five different models. The diamonds are observational data from Wolfe et al. (2008) and the plus signs are observational data from Gillmon et al. (2006). The linearly spaced contours were generated from mock observations of the simulations. They represent the distribution of surface densities and H$_2$ fractions from individual cells in a velocity cube. The first three panels compare the results of shielding-based star formation with three different methods for calculating shielding—our preferred S model, the original S$_{smooth}$ model, and a non-temperature capped Jeans length model, S$_{Jeans}$. The final two panels show the S shielding model with two different star formation models, a H$_2$-based model (H$_2$), and a temperature-capped model (TC). All models produce H I-to-H$_2$ transitions at appropriate surface densities; however, different star formation criteria allow for the presence of varying amounts of H$_2$. The S and H$_2$ simulations most successfully replicate the distribution of the H$_2$ fraction seen in the observational data. In contrast, the S$_{smooth}$, S$_{Jeans}$, and TC models result in only small amounts of high surface density material.

Figure 5. Normalized histograms of the density of star-forming gas for a galaxy formed with the S shielding model, with and without the addition of a Jeans pressure floor. The presence of a pressure floor did not significantly affect the density at which gas formed into stars.
which gas formed into stars, we were able to assess how the different star formation recipes affected the environments within which star formation occurred.

In Section 3.2, we further analyzed the effect of using H2 versus shielding-based star formation on simulations of more realistic galaxies by comparing the evolution of two cosmological dwarf galaxy simulations. These simulations were chosen to highlight the effects of the models in low-metallicity environments. We focused our analysis on the star formation within the simulations, and compared the star formation histories, Kennicutt–Schmidt relation, and stellar and gas density profiles for the simulations. Due to the computational expense, we limited our analysis of cosmological simulations to the H2 and S models.

3.1. Star-forming Gas in Isolated Simulations

Figure 6 illustrates the ISM for solar and subsolar isolated disk galaxies simulated with the TC, H2, and S star formation models. The star formation criteria has a clear effect on the structure of the gas. The H2 and S simulations led to formation of denser gas than the TC model. This effect is especially pronounced in the H2 model at solar metallicity, in which the greater amount of dense and cold gas results in the formation of more pronounced spiral arms. For all star formation models, lower metallicity gas resulted in more compact disks, because the reduced cooling efficiency prevented gas from reaching high densities, and low-metallicity gas took longer to collapse into a disk for a given initial radius.

Narrowing our focus to the star-forming gas, Figure 7 shows the temperatures and densities at which star formation occurred for all star particles in the solar and subsolar metallicity simulations. In the H2 simulation, no star formation occurred at densities below 1.0 atomic mass unit cm\(^{-3}\), and little occurred at temperatures above 1000 K, despite the lack of an explicit temperature cap. In the S simulation, however, star formation occurred at densities as low as 0.1 atomic mass units cm\(^{-3}\) and temperatures as high as 15,000 K. While explicitly limiting star formation to gas with temperatures below 1000 K, the TC model also allows for star formation at densities lower than those in the H2 model and similar to the S model. When comparing across metallicity, star formation occurred at slightly higher densities in the subsolar metallicity simulations than the solar metallicity simulations, regardless of the star formation criteria. In the subsolar metallicity gas, higher densities were required for the gas to cool, shield, or to maintain H2.

The S simulation resulted in star formation in gas with densities below 1 amu cm\(^{-3}\) and temperatures above 10\(^3\) K. Much of this material is low-density gas in thermal equilibrium that is continuing to cool. Those gas particles that are both higher density and hot include gas that, while clearly able to form stars, is not currently in thermal equilibrium because it recently experienced an injection of energy from nearby supernovae. Because of the use of a delayed-cooling feedback model, these particles may currently or until recently have had their cooling disabled.

Although we would not expect significant amounts of star formation at such low densities and high temperatures in reality, the densities and temperatures of gas particles in the simulation should be interpreted as average values for the entire gas cloud. Therefore, given the limited resolution of the simulations, these low-density, high-temperature star-forming gas particles represent clouds of gas that may contain much denser regions. Finally, the star formation in the shielding
The timescale over which gravitationally unstable gas will formation on grain surfaces would be expected from observations. The timescale for conversion of hydrogen from atomic to molecular formation occurs on the surface of dust grains, at a rate per H atom of \( n_1 \approx 1.4 \) is the mean mass per H nucleus in units of the hydrogen mass \( m_H \). The ratio of these timescales is

\[
\frac{t_{\text{chem}}}{t_{\text{ff}}} = 24Z^{-1}C^{-1}n_H^{-1/2},
\]

where \( n_H = \bar{n}_H / 1 \text{ cm}^{-3} \) (Krumholz 2012) and \( C = 10 \) for these simulations. At low metallicities, the chemical equilibrium timescale can be longer than the freefall timescale. For example, for metallicity equal to 0.1 Z\(_\odot\), \( t_{\text{chem}} > t_{\text{ff}} \) for number densities less than 580 cm\(^{-3}\). This difference in timescales suggests that, assuming H\(_2\) is not required for star formation, a cloud of gas could begin to form stars before a substantial amount of H\(_2\) is formed. In our implementation, this resulted in gas forming stars at lower density in the S model than in the H\(_2\) model. In the latter situation, the gas had to form sufficient H\(_2\) for star formation to proceed, thereby causing the gas to collapse to higher densities first. Therefore, the low-density star formation in the shielding model suggests one possible model for the small amounts of star formation that do occur in environments that have low metallicities and low average surface densities, such as dwarf galaxies and the outer disks of spiral galaxies.

### 3.2. Star Formation in Cosmological Dwarfs

We examine the impact of the shielding-based star formation prescription on the evolution of a dwarf galaxy. These simulations were chosen to highlight any differences that might occur between shielding- and H\(_2\)-based star formation in the low-metallicity, low-surface density environments of dwarf galaxies. In particular, we investigated the effect of the star formation models on the history and distribution of star formation as well as the resulting galaxy morphology.

To assess the differences in star formation among the various models, we first compared the star formation in our simulated galaxies to the observed redshift zero resolved Kennicutt–Schmidt relation (Figure 9). To replicate the observations, we calculated surface densities of H\(_1\) and H\(_2\) from mock THINGS (Walter et al. 2008) observations generated at the resolution and sensitivity for a 5 Mpc-distant dwarf galaxy. We generated data in 128 velocity channels with 1.3 km s\(^{-1}\) bins and a 1.5-arcsec pixel size for the galaxy oriented at a 45° angle. We then spatially smoothed the data cubes using a Gaussian beam with a full width at half maximum of 10 arcsec × 10 arcsec. Finally, we made a sensitivity cut and discarded all emission from cells below a 2σ noise limit, in which \( \sigma = 0.65 \) mJy beam\(^{-1}\). Star formation rates were calculated using the simulated far-UV and 24 \( \mu \)m emission generated by the radiative transfer code, SUNRISE (Jonsson 2006). Surface densities of gas and star formation were then calculated for 750\(^2\) pc\(^{-2}\) grid squares.

Both the S and H\(_2\) models produce very similar results to each other and to the observed trend for local galaxies (Bigiel et al. 2010). Both galaxies have elevated surface densities and star formation rates at their center, resulting in a data point above the observations. The scatter in the simulated data for locations beyond \( R_{25} \) is also somewhat higher than in the observed case. Otherwise, however, the data from the simulated galaxies follows the same trend as observed galaxies. While the H\(_2\) model results in slightly more high-surface-density data points than the S model, both models produce very similar relations to each other. This
similarity is in spite of the fact that the S model results in lower density gas particles forming stars. Apparently, when the surface densities are averaged over a 750$^2$ pc$^2$ grid, the comparatively high densities of the star-forming gas in the simulation with the H2 model were diluted by the surrounding interstellar media. Similar results were found in Christensen et al. (2012), where a density threshold-based star formation law produced a similar Kennicutt–Schmidt relation to the H2-based star formation law. We therefore conclude that despite the differences between the shielding and H2-based star formation models, both are consistent with the resolved Kennicutt–Schmidt relation.

One environment where shielding-based star formation might occur is in the low-metallicity outskirts of galaxies (Ferguson et al. 1998; Bigiel et al. 2010; Goddard et al. 2010). In these regions, star formation is observed to occur despite very low levels of H$_2$, and it is possible that the initial gravitational collapse for star formation might occur prior to H$_2$ formation. We therefore compare the ISM, stellar, and star formation rate surface densities as a function of radius (Figure 10). Both models produce similar gas profiles, though the H2 model does produce a higher surface density of H$_2$. Likewise, the stellar profiles are almost identical. However, we do find that the star formation rate surface density in the S model is slightly higher than in the H2 model, particularly in the outer disk, despite the lower H$_2$ surface densities.

Although the average gas surface densities were similar between the simulations produced with the H2 model and the S model, a detailed analysis of the particle densities reveals differences (Figure 11). We found that the H2 simulation produced more numerous and higher density clumps of gas than the S simulation. These clumps are evident in the figure as spatially localized spikes in the particle densities. This difference in gas densities follows from the tendency for star formation to occur in lower density gas in the S simulation. As a result, the galaxy was less able to maintain high-density clumps of material. The similarity in the average surface densities between the models, which was also apparent in the K-S law (Figure 9) and gas profile (Figure 10), camouflages these small-scale differences.

Finally, we compare the star formation across the entire history of the galaxy. The total stellar masses formed over the course of the simulations were $3.6 \times 10^9 M_\odot$ for the H2 model and $4.1 \times 10^9 M_\odot$ for the S model, indicating that the star formation recipe had a significant effect on the total mass of stars produced. This difference in stellar mass could have been
due to either or both of the following possible causes. First, star formation may have been allowed in a wider range of environments in the S simulation. From Figures 7 and 8, it is clear that the S model expands the range of gas particles capable of star formation, supporting this possibility. Second, changes to the star formation environments caused by the different models could have had other indirect effects; in particular, the efficiency of the feedback recipe may have been affected. This possibility is supported by previous research with similar simulations. For example, Governato et al. (2010) and Christensen et al. (2012) showed that the blastwave feedback recipe is most effective at regulating star formation when star formation is confined to high-density clumps. It is likely that both explanations play a role here in the total mass formed. This is also important to understand that the amount of feedback energy injected per SNe (dESN) is a tunable parameter that must be set for each combination of star formation parameters. While we used the same value of dESN for both simulations to create a fair comparison, when using either star formation model in other research, dESN would be set to ensure appropriate $\alpha = 0$ stellar masses.

Looking in more detail at the star formation histories (Figure 12), it is clear that the S model begins star formation earlier, resulting in greater amounts of star formation within the first 2 Gyr. During this early time period, the metallicity of the ISM is extremely low. Low metallicity not only increases the surface densities at which dust shielding occurs, it also decreases the rate of $\text{H}_2$ formation on dust grains. As a result, while low metallicity limits star formation in both the S and H$_2$ models, it has a stronger effect with the H$_2$ model.

After 2 Gyr, the star formation histories have a similar shape, though the star formation rate is consistently slightly higher in the S simulation. Both the H$_2$ and S recipe produce bursty star formation histories at high redshift and smoother star formation histories at low redshift. Bursty star formation histories with periods of 150–200 Myr are characteristic of present-day dwarf galaxies (Weisz et al. 2012). To resolve bursts on these timescales, we examine the star formation history over a 1 Gyr time period (Figure 12). Bursts of star formation lasting 50–100 Myr appear in both the H$_2$ and S simulations during the first gigayear but are not present in either during the latter part of the simulation, even when examining 1 kpc$^2$ subsections of the disk. Continually bursty star formation histories for dwarf galaxies are characteristic of simulations with efficient SN feedback and high star formation density thresholds (Governato et al. 2010; Hopkins et al. 2014; Shen et al. 2014; Sparre et al. 2017). Since both the H$_2$ and S simulations have these qualities, it is somewhat surprising that neither maintain bursty star formation across the entire history of the galaxies. Nevertheless, the similar shapes of the star formation histories indicate that both the H$_2$ and S star formation models are operating in a similar fashion.

4. Discussion and Conclusions

In this study we developed and analyzed an implementation for dust-shielding-based star formation in galaxy evolution simulations. We examined the effect of tying star formation probability to the amount of dust shielding, rather than the fraction of molecular hydrogen, finding that the former resulted in star formation in lower-density gas while still being consistent with the Kennicutt–Schmidt relation. We summarize our implementation and these effects below.

The shielding-based star formation model consisted of a stochastic subgrid model in which the probability of a gas particle forming a star particle was a function of the amount of dust shielding. This dependency on dust shielding replicates the theoretical model in which only shielded gas is able to achieve the low temperatures necessary for gravitational collapse. As part of the model development, different prescriptions were used for calculating the column length associated with a given gas particle. In agreement with Safranek-Shrader et al. (2017), we found that a prescription in which the column length is the Jeans length calculated with a 40 K temperature cap produced the best agreement with observations. With this prescription, we were able to replicate the observed transition from H I to H$_2$ as a function of the H I + H$_2$ surface densities calculated for the disk during post-processing.

We compared our shielding-based star formation model to a molecular hydrogen-based star formation model and a temperature ceiling model using simulations of isolated disk galaxies. The primary differences between the models were the densities and temperatures of the star-forming gas. The shielding-based model resulted in star formation at higher
temperatures and lower densities than the H$_2$-based model, while still requiring higher densities on average than a temperature ceiling recipe. One consequence of the different star-forming gas densities was the presence of denser gas in the simulation using the H$_2$ model, which also lead to more pronounced spiral structure.

The denser star-forming gas in the H$_2$ model can be explained by the time delay introduced by requiring the gas to form H$_2$ prior to star formation. During the time that the gas is forming H$_2$, it also may gravitationally collapse and reach higher densities before spawning a star particle. In models that do not rely on an explicit link between H$_2$ and star formation, the discrepancy between freefall timescales and molecular formation timescales allows star formation to begin earlier while the gas particle is at a lower density.

We further compared the shielding and H$_2$ star formation models by examining the evolution of cosmological simulations of dwarf galaxies. Both the shielding and H$_2$ models produced similar fits to the observed Kennicutt–Schmidt relation when resolved on 750 pc scales. At this resolution, differences in the densities of the star-forming gas were washed out, and both recipes provide realistic results. Despite similar gas surface density profiles, the star formation rate in the outer disk was slightly higher for the shielding simulation than the H$_2$ simulation. This difference in star formation at large radius is likely the result of shielding-based star formation being able occur at lower densities. However, the resulting stellar profiles were essentially the same for both models. Likewise, both star formation models produced similarly shaped star formation histories with similar levels of burstiness. The exception to this similarity is that star formation is able to begin slightly earlier when using the S model, because extremely low metallicity has a weaker effect on the presence of dust shielding than the amount of H$_2$. The star formation rate continued to be higher when using the S model for most of the duration of the simulation.

The strongest difference the star formation models produced in the cosmological simulations was in the total mass of stars formed. The shielding model resulted in approximately 10% more stellar mass formed over the history of the universe than the H$_2$ model. The additional stellar mass appears to be driven by a higher star formation rate in the outer disk. This difference appears to be caused not by differences in the amount of star formation per cold gas, as seen in the Kennicutt–Schmidt relation, but by the existence of greater amounts of cold gas in the H$_2$ simulation. We attribute this difference to a decrease in the effective efficiency of the SN feedback model when star formation is allowed to take place in lower density gas. Similar behavior was observed in Christensen et al. (2012), where one of the main impacts of using an H$_2$-based star formation recipe was the enhanced feedback efficiency due to star formation happening in higher density gas. The slightly lower relative efficiency of feedback observed when using the shielding model can be modulated by increasing the amount of energy released per SNe mass, $d$ESN. We therefore stress that while both dust shielding and H$_2$-based star formation models produce realistic behavior (e.g., matching the Kennicutt–Schmidt relation), the tuning of $d$ESN and other star formation or feedback models must be model specific.

While we found that the dust-shielding-based model enable star formation in lower density gas than the H$_2$-based model, there were only slight differences in the observable properties of the resulting galaxies. It is likely that these effects would be stronger in simulations that focused on the extremely early universe or that resolved the internal structure of star-forming clouds. On the resolution and timescales of cosmological galaxy formation simulations, though, the different models do not produce markedly different observable characteristics. Therefore, we conclude that both the dust-shielding-based and H$_2$-based star formation models are viable and realistic in the context of galaxy formation simulations.

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