1. INTRODUCTION

The formation of stars in disk galaxies is one of the most basic processes controlling galactic evolution. While there are many other important effects, such as galactic interactions and infall of diffuse gas, ultimately a large fraction of gas settles in rotationally supported disks, where the majority of the stellar population is born. The appearance of many galaxies is dominated by the light from massive, short-lived stars whose spatial distribution is controlled by this star formation process. The injection of heavy elements from winds and supernovae will occur mostly from this disk environment.

Empirical correlations have been found between the star formation rate (SFR), gas content, and global galactic dynamics. Based on a sample of about 100 nearby galaxies and circumnuclear starburst disks, Kennicutt (1998) found relatively simple relations between the globally averaged SFR per unit area, \( \Sigma_{\text{sfr}} \), and the total (H\textsubscript{I} and H\textsubscript{2}) gas mass surface density, \( \Sigma_{\text{gas}} \). They can be related via

\[
\Sigma_{\text{sfr}} = A_{\text{sfr}} \Sigma_{\text{gas}},
\]

with \( A_{\text{sfr}} = (2.5 \pm 0.7) \times 10^{-4} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2} \) and \( \alpha_{\text{sfr}} = 1.4 \pm 0.15 \). Alternatively, an equally good fit to the data is given by

\[
\tilde{\Sigma}_{\text{sfr}} \approx B_{\text{sfr}} \tilde{\Sigma}_{\text{gas}} \Omega_{\text{out}},
\]

where \( B_{\text{sfr}} = 0.017 \) and \( \Omega_{\text{out}} \) is the orbital angular frequency at the outer radius that is used to perform the disk averages. This last relation implies that a fixed fraction, about 10\%, of the gas is turned into stars every outer orbital timescale of the star-forming disk.

Martin & Kennicutt (2001) argued that the outer edge of the star-forming disk is set by the boundary between the gravitationally unstable \( Q \lesssim 1 \) inner disk and the gravitationally stable \( Q \gtrsim 1 \) outer region, where \( Q \) is the Toomre (1964) stability parameter

\[
Q \equiv \frac{\kappa \sigma_{g}}{\pi G \Sigma_{g}},
\]

where \( \sigma_{g} \) is the one-dimensional gas velocity dispersion in the disk plane and \( \kappa \) is the epicyclic frequency:

\[
\kappa = \sqrt{2} \frac{v_{c}}{r} \left( 1 + \frac{r}{\beta v_{c}} \right)^{1/2} = \sqrt{2} \frac{v_{c}}{r} (1 + \beta)^{1/2}.
\]

Here, \( v_{c} \) is the circular velocity at a particular galactocentric radius \( r \), and \( \beta \equiv d \ln v_{c}/d \ln r \), which is 0 for a flat rotation curve. The precise value of \( Q \) below which gas becomes unstable is also affected by the destabilizing influence of the potential due to a stellar disk (Jog & Solomon 1984; Jog 1996; Kim & Ostriker 2007). Schaye (2004) argued that the edges of star-forming disks may rather be set by the location where much of a galaxy’s atomic interstellar medium (ISM) transitions from the cold (\( \sim 300 \) K) to the warm (\( T \approx 8000 \) K) phase.

When galaxies are examined on smaller (\( \sim \text{kpc} \)) scales, e.g., by taking azimuthal averages, star formation relations similar to Equations (1) and (2) are found (Wong & Blitz 2002; Kennicutt et al. 2007; Leroy et al. 2008; Bigiel et al. 2008), although there is still debate as to whether it is the total or just the molecular gas mass that is most fundamental for controlling the SFR (Blitz & Rosolowsky 2006; Leroy et al. 2008; Bigiel et al. 2008).

1.1. GMCs: Formation, Evolution, Observed Properties

As we move to smaller scales (\( \sim 100 \) pc) we see, based mostly on surveys of CO emission in the Milky Way (Solomon et al. 1987; Dame et al. 2001; Jackson et al. 2006) that most
of the dense, cold, potentially star-forming gas is organized into giant molecular clouds (GMCs) with masses \( \sim 10^5 \, M_\odot \) and radii \( \sim 30 \, \text{pc} \) (with these particular values of mass and size corresponding to volume-averaged number densities of H nuclei of \( n_H = 260 \, \text{cm}^{-3} \) for a spherical cloud). Given that most of the Galactic molecular gas is organized in GMCs and that GMCs have approximately equal mass atomic envelopes (Blitz 1990), the results of Wolfire et al. (2003) for the radial distribution of Galactic molecular and atomic gas indicate that a large fraction, \( \sim 1/3 \), of the total gas mass in the Milky Way inside the solar circle is associated with these structures. Many questions concerning GMCs are still debated, including whether they are long or short-lived compared to their free-fall timescale,

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} = 4.35 \times 10^6 \left( \frac{n_H}{100 \, \text{cm}^{-3}} \right)^{-1/2} \, \text{yr}, \]  

and whether they are gravitationally bound (McKee & Ostriker 2007, and references therein).

Observations of GMCs are most complete in the Milky Way interior to the solar circle (Solomon et al. 1987; Williams & McKee 1997: Heyer et al. 2008). Except for the vicinity of the Galactic center, there is a dearth of clouds in the inner \( \sim 2 \, \text{kpc} \). GMCs occupy a very thin vertical distribution in the Galaxy: Bronfman et al. (2000) derived a half-intensity height of \( z_{1/2} \approx 60 \, \text{pc} \); Stark & Lee (2005) derived a vertical scale height of \( \lesssim 35 \, \text{pc} \).

Stark & Brand (1989) derived a one-dimensional cloud to cloud rms velocity dispersion of \( 7.8 \pm 0.5 \, \text{km} \, \text{s}^{-1} \) from a study of GMCs within 3 kpc of the Sun, although this estimate includes small-scale streaming motions.

Based on the \( ^{12}\text{CO} \) survey data of Solomon et al. (1987), Williams & McKee (1997) derived a cloud mass function of the form

\[ \frac{dN_c}{d\ln M_c} = N_{cu} \left( \frac{M_c}{M_\odot} \right)^{-\alpha_c}, \]

for \( M_c \leq M_{\star} \), with \( dN_c/M_c \) being the number of clouds with masses in the range \([ M_c, M_c(1 + d \ln M_c) ] \). Based on clouds in the mass range of a few \( \times 10^3 \, M_\odot \) to a few \( \times 10^5 \, M_\odot \), Williams & McKee (1997) estimated that the population of GMCs inside the solar circle is described by \( \alpha_c = 0.6 \), \( N_{cu} = 63 \), and \( M_{\star} = 6 \times 10^6 \, M_\odot \). If the observational surveys have higher degrees of incompleteness at lower masses, Williams and McKee estimated \( \alpha_c = 0.85 \), \( N_{cu} = 25 \), and \( M_{\star} = 6 \times 10^6 \, M_\odot \). Note that these mass estimates did not include any atomic gas that might be associated with the GMCs, which could be a substantial fraction (~1/2) of the total mass bound to the cloud (Blitz 1990).

The mean mass surface density, \( \Sigma_c \), of Galactic GMCs was derived by Solomon et al. (1987) to have a median value of about \( 200 \, M_\odot \, \text{pc}^{-2} \). Recently, Heyer et al. (2008) derived a median value of \( 42 \, M_\odot \, \text{pc}^{-2} \), based on a LTE analysis of \(^{13}\text{CO} \) survey data. They estimate that the true values are larger because of subthermal excitation and abundance variations and are in the range \( 80 \sim 120 \, M_\odot \, \text{pc}^{-2} \). Again these estimates do not include any atomic gas associated with the clouds.

Bertoldi & McKee (1992) define the virial parameter,

\[ \alpha_{vir} \equiv \frac{5\sigma_c^2 R_{c,A}}{GM_c}, \]

where \( \sigma_c \) is the mass-averaged one-dimensional velocity dispersion of the cloud, which includes thermal and nonthermal contributions via \( \sigma_c \equiv (\sigma_T^2 + \sigma_{\text{nth}}^2)^{1/2} \) where \( \sigma_{\text{nth}} \) is the one-dimensional rms velocity dispersion about the cloud’s center-of-mass velocity, and \( R_{c,A} \) is a measure of cloud radius based on its projected area. The virial parameter is a measure of the ratio of the kinetic to gravitational energy of a cloud. For a uniform, spherical cloud, \( \alpha_{vir} = 1 \) implies the total kinetic energy of the cloud is half the magnitude of the gravitational energy. Non-spherical and nonuniform density distributions typically make only modest effects, parameterized via the dimensionless factor \( a \) in the gravitational energy equation \( W = -(3/5)aGM_c^2/R_{c,A} \); Bertoldi & McKee (1992) estimate that cloud major to minor axis ratios of a factor of 3 only cause \( a \) to deviate from unity by \( \lesssim 10\% \), while a power-law density profile \( \rho \propto r^{-3/2} \) results in \( a \approx 1.25 \). Observationally, Heyer et al. (2008) find a median value of \( \alpha_{vir} \) of about unity.

Phillips (1999) considered the rotational properties of Galactic GMCs, finding a significant spread in the directions of the angular momentum vectors (as derived from radial velocity gradients and as projected on the plane of the sky), indicating that a substantial fraction of GMCs rotate in a retrograde direction with respect to Galactic rotation.

Observations of GMCs in other galaxies tend to find they have similar properties as Galactic GMCs, including their velocity dispersions and virial parameters (Bolatto et al. 2008). Rosolowsky et al. (2003) measured the rotational properties of large GMCs in M33, finding relatively small values of specific angular momentum, and a substantial population (\(~40\%) of clouds with rotation directions retrograde with respect to that of the galaxy. Fukui et al. (2008) studied 164 GMCs in the Large Magellanic Cloud, concluding that these clouds were also close to virial equilibrium.

The star formation activity within GMCs appears highly clustered. Most stars are born in star-forming clumps that turn into star clusters (Lada & Lada 2003), with initial radii \( \sim 1 \, \text{pc} \). Here, the local overall star formation efficiency is relatively high, \( \epsilon_s \equiv M_\star/M_{\text{gas}} \sim 0.1 \sim 0.5 \), where \( M_\star \) is the total mass of stars formed from the mass of gas \( M_{\text{gas}} \) that occupies the same volume as forming star cluster. Conversely, most of the volume of GMCs is not actively forming stars, perhaps because of magnetic field support (Crutcher 2005).

Theoretical work on the formation of GMCs has led to different schools of thought (McKee & Ostriker 2007, and references therein). “Top-down” formation mechanisms suggest that GMCs form via large-scale gravitational or magnetic disk instabilities (e.g., Kim et al. 2003; Shetty & Ostriker 2006; Glover & Mac Low 2007a, 2007b), whereas “bottom–up” processes have GMCs forming via agglomeration from inelastic collisions of clouds (e.g., Kwan 1979) or from turbulent or colliding flows (e.g., Bergin et al. 2004; Heitsch et al. 2008). It is possible that both processes may be important depending on the galactic environment (Dobbs 2008). If GMCs are relatively long-lived and contain a large fraction of the total ISM, then the formation and destruction of GMCs to and from the atomic phase may be less important than the interactions between those already existing (Tan 2000): in other words, the nature of a particular cloud may change more drastically via merging collisions with other GMCs than via flows into or out of the atomic phase.

In this paper, as a first step toward understanding galactic SFRs, we will examine the formation and evolution of GMCs in the context of the global dynamics of a flat rotational curve disk galaxy.

1.2. Theories of Disk Galaxy Star Formation Rates

Numerous theories have been proposed to explain the observed galaxy-scale, Kennicutt star formation relations. One group of theories is based on the growth rate of gravitational per-
turbations in a disk. The timescale for perturbation growth can be expressed as $t_{\text{grow}} \propto (G\rho_p)^{-0.5}$ (e.g., Larson 1988; Elmegreen 1994; Wang & Silk 1994), and so $t_{\text{grow}} \propto \rho_p/t_{\text{grow}} \propto \rho_p^{1.5}$. Assuming a constant disk scale height, we obtain Equation (1) with $\alpha_{\text{ef}} = 1.5$ for local mass surface densities. However, disk-averaged quantities will depend on the radial gas distribution. We can also express $t_{\text{grow}} \propto \rho_p/(\pi\Sigma) \propto Q/\kappa$. Perturbation growth via swing amplification in a differentially rotating disk occurs at a similar rate (e.g., Larson 1988). By assuming that star formation self-regulates and keeps $Q$ constant, Larson (1988) and Wang & Silk (1994) predicted $\Sigma_{\text{sfr}} \propto \Sigma_g/t_{\text{grow}} \propto \Sigma_g \Omega$, since $\kappa \propto \Omega$, for disks with flat rotation curves. Li et al. (2006) presented isothermal smooth particle hydrodynamic (SPH) simulations of disk galaxies, from which they concluded that the rate of the nonlinear development of gravitational instability determines the local and global Kennicutt relations.

However, these theories that involve the SFR being set by the growth rate of large-scale gravitational instabilities leading to GMC formation, have difficulty in explaining why a large mass fraction of the gas is already organized into GMCs. If the GMCs are forming rapidly in $\sim 1$ dynamical timescale the mass flux into (and out of) GMCs would be $\sim 100$ times greater than that from GMCs into star clusters (Zuckerman & Evans 1974). To understand global SFRs, it seems more reasonable to look for processes that create the star-forming parsec-scale clumps within GMCs, rather than the processes that create the GMCs themselves.

The spatial correlation of star formation with large-scale spiral structure in some disk galaxies motivates theories for the triggering of star formation during the passage of gas through density waves. Wyse (1986) and Wyse & Silk (1989) propose a SFR law of the form

$$\Sigma_{\text{sfr}} \propto \Sigma_g^{5/4}(\Omega - \Omega_p), \quad (8)$$

where $\Omega_p$ is the pattern frequency of the spiral density wave. In the limit of small $\Omega_p$, and for $\alpha_{\text{ef}} = 1$ we recover Equation (2). Increased cloud collision rates and increased perturbation growth rates in the arms, where $Q$ is locally lowered, have been suggested as the star formation triggering mechanism (e.g., Dobbs 2008). Kim et al. (2008) examined the development of thermal instabilities in galactic spiral shocks.

One prediction of these theories is a correlation of SFR with the density wave amplitude. However, this is not observed (Elmegreen & Elmegreen 1986; McCall & Schmidt 1986; Kennicutt 1989). Furthermore, such theories have difficulty explaining star formation in galaxies where there is a lack of organized star formation features, as in flocculent spirals (e.g., Thornley & Mundy 1997a, 1997b; Grosbol & Patsis 1998). GMCs are present and SFRs are similar to those systems where star formation is organized into spiral patterns. This suggests stellar disk instabilities, which create spiral density waves, and gas instabilities, which lead to GMCs and large-scale star formation, are decoupled (Kennicutt 1989; Seiden & Schmalman 1990).

Tan (2000) proposed a model in which the majority of star formation in disk galaxies occurs in the pressurized regions triggered by GMC–GMC collisions. GMCs are observed to occupy a very thin vertical distribution in the Galaxy (Stark & Lee 2005), which is similar to the actual sizes of the clouds. In this effectively two-dimensional system, collisions are set by galactic shear at impact parameters of about the tidal radius of the clouds (Gammie et al. 1991), and for a $Q \sim 1$ disk with a relatively large mass fraction, $\sim 1/2$, in GMCs and associated gas, collisions are expected to occur approximately every 20% of an orbital time. In this way, for flat rotation curve galaxies, Equation (2) is recovered, and the cloud collision mechanism is the link between the global galactic dynamics and the parsec-scale star-forming clumps of GMCs. One prediction of this model is a reduction in the SFR per orbital time for galaxies with lower rates of shear, i.e., those with rising rotation curves that are closer to solid body rotation. This model also requires GMCs to be relatively long-lived, i.e., several tens of Myr.

Krumholz & McKee (2005) proposed that the SFR is regulated by turbulence in a galaxy’s molecular gas, so that a fixed fraction of the turbulent, molecular gas is converted to stars per free-fall time of the GMC. To recover Equation (2), one has to assume that GMC dynamical timescales are a fixed fraction of galactic dynamical timescales and that GMC mass fractions are constant in different galactic systems (see also Wada & Norman 2007).

### 1.3. Numerical Studies of GMC Formation and Disk SFRs

The large range of spatial scales involved from GMCs to global galactic properties (a range of $\sim 10^4$ from $\lesssim 10$ parsec-scale clouds to the galactic scale) has made it extremely difficult for simulations to encompass GMC formation on global scales. Work that does perform this is either limited to two dimensions (Shetty & Ostriker 2008) or has to assume a fixed two-phase medium for the ISM (Dobbs 2008). While the clouds do largely reside in the plane of the disk (which is in essence a twodimensional system), cloud collisions and feedback can eject gas from the surface, a process that controls the pressure of the ISM from which the clouds are forming (McKee & Ostriker 1977; Cox 2005). Similarly, a fixed phase ISM results in clouds being created from gas with a predetermined structure, from which it is harder to discern the main physical effects controlling their formation and evolution. Three-dimensional models that contained a self-consistent multiphase atomic ISM on global scales were performed by Tasker & Bryan (2006, 2008) and Wada & Norman (2007), but either did not reach the resolution needed to probe below the most massive GMCs (e.g., the simulations of Tasker & Bryan 2008) had a limiting resolution of $25$–$50$ pc), or only considered the inner galaxy (e.g., the simulations of Wada & Norman 2007) were restricted to $r < 2.56$ kpc). Robertson & Kravtsov (2008) presented a global SPH simulation, with similar effective resolution to the simulation of Tasker & Bryan (2008) (A. V. Kravtsov 2008, private communication) of star formation in disk galaxies including a multiphase ISM, and subgrid models for various forms of stellar feedback and molecular hydrogen formation and destruction (see also Gnedin et al. 2009).

Local models can resolve down to smaller scales and, if set up in a shearing box, can approximate the effects of galactic shear on cloud formation and evolution (e.g., Kim & Ostriker 2001, 2006, 2007). Other examples of local models have focused on cloud formation from imposed colliding flows (e.g., Heitsch et al. 2008), including the effects of magnetic fields (Heitsch et al. 2009). Other groups have studied cloud formation in the context of the local interplay between supernova feedback and a turbulent, multiphase ISM (e.g., Slyz et al. 2005). Simulations including the nonequilibrium formation and destruction of H$_2$ molecules have been carried out by Glover & Mac Low (2007a, 2007b).

While these local models are very important for studying many aspects of GMC formation and evolution, they cannot explore the global evolution of GMCs as they orbit through the
disk or measure how GMC (and star formation) properties are related to the more readily observed global galactic properties such as mean gas mass surface density. Trends with galactocentric radius are also easier to study in global models.

In this paper, we present results from a three-dimensional global galaxy (~32 kpc box containing a gravitationally unstable galactic disk with diameter 20 kpc) simulation that tracks the formation and evolution of clouds in a self-consistent multiphase atomic ISM. Our main simulation has a limiting resolution of 7.8 pc. As discussed below, we do not at this stage include the physics of star formation and feedback. We also do not include magnetic fields, cooling below 300 K, or any treatment of the formation and destruction of molecules. Our definition of “GMCs,” which we also refer to interchangeably as “clouds,” is discussed in detail below, but basically involves a density threshold of \( n_\text{H} \geq 100 \text{ cm}^{-3} \). In real galaxies, the structures that correspond to this definition will typically be composed of a mixture of atomic and molecular gas, but we argue that the bulk dynamical properties of the clouds can still be reasonably well captured by our simulations.

2. NUMERICAL TECHNIQUES

2.1. The Code

The simulations performed in this paper were run using Enzo: a three-dimensional adaptive mesh refinement (AMR) hydrodynamics code (Bryan & Norman 1997; Bryan 1999; O’Shea et al. 2004). Enzo has been used previously in galactic disk simulations (e.g., Tasker & Bryan 2006, 2008), where it successfully produced a self-consistent multiphase atomic ISM, consisting of a wide range of densities and temperatures. Grid codes are particularly adept at modeling multiphase gases since the grid cells form natural boundaries allowing the gas to evolve with a range of temperatures, densities, and pressures. Particle-based techniques also struggle to resolve fluid instabilities (Tasker et al. 2008) and can suffer from overmixing problems unless specific algorithmic steps are taken.

Enzo evolved the gas using a three-dimensional version of the Zeus hydrodynamics algorithm (Stone & Norman 1992). This scheme uses an artificial viscosity term to model shocks and the variable associated with this, the quadratic artificial viscosity, was set to 2.0 (the default) for all simulations. Radiative gas cooling followed the solar metallicity cooling curve of (Sarazin & White 1987) down to temperatures of \( T = 10^4 \text{ K} \) and extends down to \( T = 300 \text{ K} \) using rates from Rosen & Bregman (1995). These temperatures take us to the upper end of the atomic cold neutral medium (Wolfire et al. 2003). In this study, we do not include the formation and destruction of molecules or any cooling processes below 300 K. By a combination of dust and molecular cooling, gas in real GMCs reaches temperatures of \( \sim 10^5 \text{ K} \), more than an order of magnitude below our minimum radiative cooling temperature. However, since we are not able to resolve the detailed internal structure of clouds and their internal turbulence (a typical cloud with a diameter of \( \sim 100 \text{ pc} \) would only have \( \sim 13 \) cells across each linear dimension in our highest resolution simulation) and since we are not including magnetic pressure support, we view our temperature floor of 300 K as being equivalent to imposing a minimum one-dimensional signal speed equal to the sound speed \( c_s = (\gamma P/\rho)^{1/2} = (\gamma kT/\mu)^{1/2} = 1.80(T/300 \text{ K})^{1/2} \text{ km s}^{-1} \), where \( \gamma = 5/3 \), \( \mu = 1.273m_p \) (for an assumed \( n_{\text{H}_2} = 0.1n_{\text{H}_2} \)). This signal speed is somewhat smaller than observed internal velocity dispersions of GMCs. In fact we will see that, even though our simulation does not include feedback, our simulated GMCs typically attain internal nonthermal (i.e., turbulent) velocity dispersions much greater than this minimum.

The galaxy was modeled in a three-dimensional simulation box of side 32 kpc with isolated gravitational boundary conditions and outflow fluid boundaries. For our main, high-resolution simulation, the root grid was 256\(^3\) with an additional four levels of refinement, producing a minimum cell size of 7.8 pc. To examine how simulation results depend on resolution, we also carried out medium and low-resolution runs with a minimum cell sizes of 15.6 pc and 31.2 pc, respectively. Refinement of a cell occurred when the Jeans length drops below four cell widths, in accordance with the criteria suggested by Truelove et al. (1997) for resolving gravitational instabilities. Resolution of the fragmentation is discussed further in Section 2.4. The disk was allowed to evolve for 324 Myr, about 1.3 orbital periods at \( r = 8.0 \text{ kpc} \) (see Section 2.2) and substantially longer than the local free-fall time of the initial mid-plane gas at this location, which was about 60 Myr.

In this paper, the first of a series, we examine the formation and evolution of GMCs in a flat rotation curve galactic disk without the presence of star formation and feedback mechanisms, which we defer to future papers. Since the amount of mass removed by star formation is expected to be only a few percent per local free-fall time (Zuckerman & Evans 1974; Krumholz & Tan 2007), the gas depletion over the course of the simulation time would be relatively modest. The structure of the ISM and the GMC population we derive can be regarded as that resulting from the limiting case when there is very little coupling of stellar feedback (including FUV heating) to the ISM. Gravitational scattering of bound clouds in a shearing disk and dissipative cloud collisions are the processes that will act in our simulations to extract orbital energy and regulate the ISM structure.

2.2. The Initial Structure of the Galactic Disk

To mimic the present-day Milky Way, the simulated galaxy was set up as an isolated disk of gas orbiting in a static background potential which represented both dark matter and a stellar disk component. This minimized the effects from the evolution of the galaxy on the interstellar structure, allowing us to investigate the formation and evolution of GMCs in a steady-state environment. The background potential was chosen to produce a flat rotation curve at \( r \gg r_c \), where the core radius was set to be \( r_c = 0.5 \text{ kpc} \). The form of the potential is (Binney & Tremaine 1987)

\[
\Phi = \frac{1}{2} v_{c,0}^2 \ln \left[ \frac{1}{r^2} \left( \frac{r^2 + r^2 + z^2}{q_0^2} \right) \right], \tag{9}
\]

where \( v_{c,0} \) is the constant circular velocity in the limit of large radii, here set equal to 200 km s\(^{-1}\), \( r \) and \( z \) are the radial and vertical coordinates, respectively, and the axial ratio of the potential field is \( q_0 = 0.7 \). The form of the circular velocity of the disk, \( v_c \), is then given by

\[
v_c = \frac{v_{c,0} r}{\sqrt{r^2 + r^2}}. \tag{10}
\]

The initial radial profile of the gas mass surface density in the disk was chosen to give a constant value of the Toomre \( Q \) parameter for gravitational instability (Toomre 1964):

\[
\Sigma_r = \frac{k \sigma_{r,0}^2}{\pi G Q}. \tag{11}
\]
where \( \sigma_g \), the one-dimensional velocity dispersion of the gas, is equivalent to the sound speed \( c_s \) for the case of an razor thin disk with only thermal pressure. The particular choices of \( Q \) at different radii are discussed below. For our simulated gas disk we define \( \sigma_g \equiv \left( \sigma^2 + c^2_s \right)^{1/2} \), averaged over the mass in particular regions of the disk, where \( \sigma_m \) is the one-dimensional velocity dispersion of the gas motions in the plane of the disk after the subtraction of the circular velocity, i.e., representing nonthermal motions. Our disks are initialized with \( \sigma_m = 0 \).

The initial vertical profile of the gas was set proportional to \( \text{sech}^2(z/zh) \), where \( zh \) is the vertical scale height, which was assumed to vary, i.e., increase, with galactocentric radius based on observations of the H I in the Milky Way presented in Binney & Merrifield (1998). At the solar radius of 8 kpc, \( zh = 290 \) pc. Then we have \( \Sigma_{g} = \int_{-\infty}^{\infty} \rho_0 \ \text{sech}^2(z/zh)dz = 2\rho_0zh \), where \( \rho_0 \) is the midplane (\( z = 0 \)) density, so that the gas distribution becomes

\[
\rho(r, z) = \frac{k \sigma_g}{2\pi G Q^2 zh} \text{sech}^2 \left( \frac{z}{zh} \right).
\]

The initial disk profile is divided radially into three sections. In our main region of interest, between radii of \( r = 2 - 10 \) kpc (that is, encompassing the part of the Galaxy inside the solar circle with radius of 8 kpc) \( \Sigma_{g} \) is set so that \( Q = 1 \) if \( \sigma_g = c_s \) were equal to 6 km s\(^{-1}\), similar to the observed velocity dispersion of the ISM (Kennicutt 1998; Stark & Brand 1989).

The actual initial velocity dispersion (i.e., sound speed) is set to \( c_s = 9.0 \) km s\(^{-1}\), so that \( t_{\text{init}} \sim 7450 \) K and \( Q = 1.5 \). The threshold of gravitational instability is crossed by allowing the gas to cool. The other regions of the galaxy, from 0 to 2 kpc and from 10 to 12 kpc, are initialized in a similar way, but are designed to be gravitationally stable with \( Q = 20 \) for a flat rotation curve in \( c_s = 6 \) km s\(^{-1}\) (although note the rotation curve is not flat in the center). Their initial temperatures are set to the same value as in the main disk region. Even after cooling to the temperature floor of 300 K, for which \( c_s = 1.8 \) km s\(^{-1}\), these regions remain gravitationally stable, except for a small amount of gas that collects at the galaxy center. Beyond 12 kpc, the disk is surrounded by a static, very low density medium, that has negligible influence. Only the main disk region from 2 to 10 kpc is analyzed in this paper, and in fact, due to boundary effects, we typically restrict analysis to radii from 2.5 to 8.5 kpc.

In total, the gas mass was \( 6 \times 10^9 \) M\(_\odot\). Note, this is a factor of 10 smaller than the disks presented in Tasker & Bryan (2008).

### 2.3. Defining and Analyzing Giant Molecular Clouds

The clouds in the galactic disk were located using a number density of H nuclei threshold of \( n_{H,c} = 100 \) cm\(^{-3}\), similar to the mean (volume-averaged) densities of typical Galactic GMCs. Also recall that the formation of molecules is not being followed in this simulation. When we refer to “clouds” or “GMCs” we are describing the gas that has achieved densities of \( n_H \geq n_{H,c} \) in the atomic phase. We expect that most of the gas above this density would form molecules via surface reactions on dust grains, although there could still be substantial (\( \sim \) equal mass) atomic components present, as are observed in and around Galactic GMCs (Wannier et al. 1991; Blitz 1990).

The process of locating and tracking the clouds in the disk at a given time in the simulation is outlined below.

1. Clouds were identified as peaks in the baryon density field with \( n_H \geq n_{H,c} = 100 \) cm\(^{-3}\). If two peaks were \( \leq 4 \) minimum cell widths apart, i.e., about 30 pc in our high-resolution run, then only the higher density peak was retained for cloud definition.

2. Nonpeak cells with \( n_H \geq n_{H,c} \) were assigned to the nearest peak that was connected to them by cells with \( n_H \geq n_{H,c} \), i.e., clouds are continuous structures.

Once the cloud had been defined, properties including the cloud’s center of mass, velocity, and angular momentum were calculated. Multiple could exist in the same continuous density structure if it contained more than one well-separated peak.

To follow the evolution of the clouds, simulation outputs were analyzed every 1 Myr and the clouds mapped between outputs with a tag number assigned to each cloud to follow its life through the simulation. To map a cloud between times \( t_0 \) and \( t_1 \), the code performed the following steps.

1. Assuming linear motion, a predicted position of each cloud’s center of mass found at time \( t_0 \) is calculated for the cloud at \( t_1 \).

2. A volume of radius 50 pc, larger than the expected deviations from linear motion due to typical accelerations (e.g., over 1 Myr these are about 20 pc at \( r = 2 \) kpc due accelerations in the galactic potential), centered on the predicted position of each cloud is searched for clouds present at time \( t_1 \). If multiple clouds are found in this region at \( t_1 \), the nearest one is chosen to be associated with the cloud from \( t_0 \).

3. In cases where two or more \( t_0 \) clouds are associated with the same \( t_1 \) cloud, the nearest one is matched and the volume around the predicted positions of the other \( t_0 \) clouds is searched for alternative candidates.

4. If no clouds at \( t_1 \) are associated with a \( t_0 \) cloud, then a volume with radius equal to 3 \times the average radius of the \( t_0 \) cloud is searched. This allows for large, extended clouds whose radius may be \( \gtrsim 50 \) pc and whose centers may have shifted due to external perturbations.

5. Any \( t_0 \) clouds remaining unassigned may have merged with neighboring \( t_0 \) clouds. A volume of radius 2 \times the average radius of each \( t_0 \) cloud is searched for unassigned \( t_0 \) clouds. This value was chosen to be lower than for the previous step since a recently merged cloud is likely to be fairly extended. If found, a merger is declared between the \( t_0 \) cloud previously associated with the \( t_1 \) cloud and the unassigned \( t_0 \) cloud. The \( t_1 \) cloud inherits the tag number from the more massive of the two merged clouds. If there were multiple \( t_1 \) clouds close to an unassigned \( t_0 \) cloud, the closest was chosen. Multiple mergers involving more than two clouds were possible, though were typically rare.

6. Any \( t_0 \) clouds remaining unassigned after these steps are declared to have been destroyed by nonmerger processes.

Note that this method assumes that any cloud that has been destroyed in close proximity to another cloud has suffered a merger. This assumption works well in the current simulation, which has no stellar feedback, but it remains to be tested once feedback processes are operating.

Figure 1 illustrates two possible examples of the cloud mapping. The blue circles show clouds at \( t = t_0 \) and the red circles show clouds located 1 Myr later at \( t = t_1 \). In panel (A), the predicted position of cloud 1 at \( t = t_1 \) is marked by the black dotted open circle. The surrounding region with radius 50 pc is searched for clouds present at \( t_1 \) and two are found. The closest of these is identified to be cloud 1 at \( t_1 \) whereas the other cloud is either a newly formed cloud or a different cloud present at \( t_0 \). Panel (B) shows how the algorithm deals with a
Figure 1. Diagram to illustrate how clouds are tracked from one output time step to the next, typically 1 Myr later. Panel (A) shows a simple example: the predicted position (center of mass) of cloud 1 at time $t_1$ is shown by the black dotted circle. A volume of radius 50 pc is searched for clouds present at $t_1$ and the nearest cloud is tagged as being cloud 1 at time $t_1$. Panel (B) shows a more complex scenario where two clouds present at time $t_0$ merge to form a single cloud at time $t_1$ (diagram is illustrative and not to scale).

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

more complex situation involving a merger. Here, a cloud at $t_1$ is associated with both $t_0$ clouds 2 and 3. The code checks there are no unassigned clouds at $t_1$ that are a viable match for cloud 2 or 3 but finding none, it declares this a merger event. Note that the cloud detection algorithm does not allow distinct clouds to be found within four minimum cell widths of each other.

Figure 2 shows how the cloud identification and tracking work in the simulation. The two images show the gas density in a one-cell thick slice of a square patch of the galaxy disk midplane 2 kpc across and 5 kpc from the galactic center, taken 1 Myr apart. Contour lines mark the density threshold of $n_{H_2} \geq 100 \text{ cm}^{-3}$ and the squares and triangles (prograde and retrograde rotators, see Section 4.2) show the center of mass of each of the clouds identified, with their tag number written below. Areas where contours or a peak appear to be visible without a cloud are due to the cloud’s center of mass being above or below the slice shown. The cloud tracking algorithm correctly maps clouds between the two outputs and shows an evolution of clouds 9282 and 13580 on the right-hand side.

2.4. Resolving Gravitational Collapse

Finite computational resources impose a limit on the number of levels of refinement we are able to employ in the simulation. Cells at the highest level of refinement are themselves not refined further, which means they can grow in mass and density to the limit of the computational resources. The fragmentation of the main disk begins at the inner part of this region, not only because the cooling occurs faster in this denser region, but also because once gravitationally unstable structures have formed, being denser they collapse with shorter free-fall times. By $t \sim 140$ Myr the main region of the disk, i.e., out to $\sim 8.5$ kpc, has fully fragmented.

Once formed, clouds start to interact as differential rotation in the disk brings them into contact with one another, and again this evolution occurs more rapidly in the inner regions of the disk. GMCs may suffer spurious fragmentation in the simulation, however it should be noted that these GMCs typically have internal velocity dispersions that are much larger than the sound speed (see Section 4.2). We examine the effect of simulation resolution on the GMC mass function and other properties in Section 4.2.

3. GLOBAL ISM STRUCTURE AND EVOLUTION

The evolution of the disk is shown in Figures 4 and 5. Starting with a velocity dispersion of $\sigma_g = 5 \text{ km s}^{-1}$ (i.e., at a temperature of 7450 K) the disk is gravitationally stable. The gas cools relatively quickly, lowering the sound speed to below 6 km s$^{-1}$, at which point $Q < 1$ in the main disk region. This cooling occurs most rapidly in the denser inner regions.

The first structure to form is an overdense ring near the inner boundary of the main disk at $r = 2$ kpc. The formation of this structure is influenced by the boundary condition of the inner edge of the main disk, i.e., the relative lack of gas inside 2 kpc. The Toomre ring instability gathers material radially from a scale about equal to the Toomre length, $\lambda_T = 2\pi^2 G \Sigma_c / \kappa^2$ (the numerical coefficient applies for infinitely thin gas disks), i.e., the most unstable scale. Similar ring structures form slightly later just outside the inner ring and also at the outer edge of the disk. These rings then fragment azimuthally into clouds. To avoid structures being influenced by the boundaries of the main disk, we restrict our cloud analysis to clouds that form between 2.5 and 8.5 kpc.

The fragmentations of the main disk begins at the inner part of this region, not only because the cooling occurs faster in this denser region, but also because once gravitationally unstable structures have formed, being denser they collapse with shorter free-fall times. By $t \sim 140$ Myr the main region of the disk, i.e., out to $\sim 8.5$ kpc, has fully fragmented.

Once formed, clouds start to interact as differential rotation in the disk brings them into contact with one another, and again this evolution occurs more rapidly in the inner regions of the disk. Gammie et al. (1991) investigated this process analytically and with numerical integrations of binary collisions and cloud
Figure 2. Example of cloud tracking in the medium resolution (15.6 pc) simulation. The left panel shows a 2 kpc square patch of the galactic plane, 5 kpc from the galactic center, at $t = 160$ Myr, 15.6 pc thick in the $z$-direction, with the gray scale showing column density through this slice, i.e., proportional to $n_{\text{H}}$ in the cells. Contours show the cloud definition threshold density of $n_{\text{H},c} = 100$ cm$^{-3}$, while the numbered squares and triangles show the center-of-mass position of the clouds located inside the volume of the slice with prograde and retrograde rotation, respectively. The right panel shows the same patch at $t = 161$ Myr. Galactic orbital motion has carried clouds and the ISM structure upward and to the left. The cloud tracking algorithm successfully tracks clouds as they move, and records a merger of clouds 9282 and 13550 on the right side of the images. Note that the center of mass of cloud 13155 enters the slice from above during this time interval, just lower-left of center of the image.

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

interactions, finding interaction times that are a fraction of the orbital time. We investigate the cloud collision time in more detail in Section 4.1.

Outside the main disk region, the low density gas remains stable. The very center of the disk, $r < 2$ kpc, does show some development of overdense structures. This is due to the infall of gas to the galactic center, most likely due to numerical viscosity resulting from the use of a Cartesian grid to simulate small-scale circular gas motions. These inner regions are excluded from our analysis.

Azimuthally averaged radial profiles of $\Sigma_g$, $\sigma_g$, $T$, and $Q$ are shown in Figure 5. Note that here we show $\Sigma_g = \int_{-1\text{kpc}}^{+1\text{kpc}} \rho(z)dz$, which is effectively equal to the full vertical mass surface density through the simulation box, $\sigma_g$ is a mass-weighted average over $-1$ kpc $< z < 1$ kpc utilizing only disk plane velocity components, $T$ is a mass-weighted average over $-1$ kpc $< z < 1$ kpc and $Q$ makes use of $\Sigma_g$ and $\sigma_g$ via Equation (3).

In the main disk, away from the boundaries, the mean value of $\Sigma_g$ at a particular radius does not change very much during the course of the simulation. Small-scale fluctuations due to ring instabilities are prominent at early times, but become smoothed out as the rings fragment into clouds, which then gravitationally scatter off of each other.

During the early stage of the simulation, the gas cools rapidly, which causes $Q$ to drop below the threshold for instability. The gas is also contracting vertically toward the disk midplane. After about 50 Myr, the bulk properties of the main disk remain relatively constant for some time, since the temperature floor of 300 K has been reached for much of the disk material. At later times, after the disk has fragmented into clouds and they...
start interacting gravitationally, there is a significant increase in the velocity dispersion of the gas and some heating. At late times the Toomre stability parameter rises to values above unity, because of the strong gravitational scattering of clouds.

Figure 6 shows the probability distribution function (PDF) for gas density. The top panel shows the volume-weighted PDF, evaluated over a volume extending radially from 2.5 to 8.5 kpc and ±1 kpc above and below the disk midplane. The mass-weighted PDF is shown in the bottom panel. These figures show the relatively fast evolution from the initial conditions caused by the early cooling and fragmentation. Evolution after 100 Myr proceeds more slowly: there is very little change from 200 to 300 Myr.

Figure 6 also shows a fit of a log-normal distribution, \( p(\ln x) = (2\pi \sigma_{PDF}^2)^{-1/2} \exp(-0.5\sigma_{PDF}^2 (\ln x - \ln \langle x \rangle)^2) \), where \( x = \rho/\bar{\rho} \), to the volume-weighted PDF at the densities relevant to clouds (see also Wada & Norman 2007; Tasker & Bryan 2008). Since we are only fitting to a portion of the PDF, here we are only interested in the width of the distribution, \( \sigma_{PDF} \), not the normalization. We find \( \sigma_{PDF} = 2.0 \). Following the empirical relation \( \sigma_{PDF} \approx \ln[1 + (3M^2/4)] \) derived from analysis of simulations of isothermal, non-self-gravitating supersonic turbulence (Padoan et al. 1997; Padoan & Nordlund 2002; Krumholz & McKee 2005), where \( M \) is the one-dimensional Mach number, we estimate \( M \approx 8.5 \). For a sound speed of 1.80 km s\(^{-1}\), this corresponds to a velocity dispersion of 15 km s\(^{-1}\), about 50% larger than the typical internal velocity dispersions of clouds (Section 4.2) or the disk-mass-averaged velocity dispersions (Figure 5). This moderate discrepancy may be due to self-gravity skewing the high-side of the PDF and/or the effects of shearing streaming motions in the disk, which are removed from the disk-averaged velocity dispersions.

The density-temperature phase space of the ISM is shown in Figure 7. In the top row, the contours are related to the volume in the simulation at the given densities and temperatures. After disk fragmentation, most of the volume is at low densities, \( n_H \sim 10^{-5} \) cm\(^{-3}\), and high temperatures, \( T \sim 10^5 \) K. The temperature floor of the cooling curve at 300 K is evident on the left-hand side of these diagrams: most of the GMC material is at this effective temperature, i.e., has an effective sound speed of 1.8 km s\(^{-1}\), and these clouds occupy very little volume. Note that cooler temperatures are possible via adiabatic cooling. In the bottom row, the contours are related to the mass in the simulation at the given densities and temperatures. Most mass is in high density, \( n_H \sim 1-1000 \) cm\(^{-3}\), structures, including our defined “GMCs” with \( n_H \geq 100 \) cm\(^{-3}\).

The typical local Milky Way total diffuse ISM pressure is about \( 2.8 \times 10^4 \) K cm\(^{-3}\) and its thermal components are about an order of magnitude smaller (Boulares & Cox 1990). These pressures are shown by straight lines in Figure 7. Our simulated diffuse ISM is at significantly lower pressures compared to the observed Milky Way pressures. This is not surprising since this simulation does not include feedback from star formation, including FUV heating, stellar winds, ionization, and supernovae. Nevertheless, much of the volume of the simulated ISM is in approximate pressure equilibrium. The pressure is set by energy input from hot gas produced in shocks resulting from cloud–cloud collisions. GMCs in the simulation are at much higher pressures than the diffuse ISM, due to their self-gravity (see below). In fact the thermal pressure of the cloud threshold density at the minimum cooling temperature is about equal to
the mean total pressure in the local Milky Way ISM observed by Boulares & Cox (1990).

4. GMC PROPERTIES AND EVOLUTION

4.1. GMC Formation and Merger Rates

As the disk becomes gravitationally unstable, local patches increase in density, many of which reach our threshold value of $n_{H,c} = 100$ cm$^{-3}$, at which point we recognize them as a GMC. The formation rate of these clouds over the course of the simulation is shown in Figure 8. There is a burst of cloud formation associated with the initial fragmentation of the disk, with the rate peaking at about 400 Myr$^{-1}$ at a simulation time of $t = 100$ Myr. By $t = 140$ Myr, cloud formation settles down to a slower and nearly constant rate of $\sim 200$ Myr$^{-1}$. This is partly due to there being a smaller noncloud diffuse gas reservoir and partly due to heating of the disk by gravitational interactions of the cloud population. We are most interested in the cloud and ISM properties after $t = 140$ Myr, since before this time their properties are influenced by the artificially smooth initial conditions and their fragmentation via the Toomre ring instability.

Figure 8 also shows the evolution of the total number of clouds and the merger rate of clouds. This information is used to calculate the mean merger time of clouds, $t_{\text{merger}}$, relative to their orbital time, as a function of galactocentric radius (Figure 9). This calculation assumes mergers are all binary mergers (the non-binary merger fraction is indeed negligibly small). From Figure 9 we see that the average merger time settles to be a small fraction, $\sim 0.2$, of the orbital time, with only a modest dependence on galactocentric radius and simulation time for $t \geq 140$ Myr. This confirms the results of Tan (2000), who estimated $t_{\text{merger}}/t_{\text{orbit}} = 0.2$ based on the simplified calculation of cloud orbits and binary interactions by Gammie et al. (1991). Note that the orbital time for $v_c/v_{c,0} = 200$ km s$^{-1}$ is

$$t_{\text{orbit}} = 123(r/4 \text{ kpc})(v_c/200 \text{ km s}^{-1})^{-1} \text{Myr},$$

(13)

so that the typical merger time is only $\sim 25$ Myr, which is relatively short compared to traditional estimates of cloud collision timescales of hundreds of Myr that do not allow for the essentially two-dimensional geometry of the GMC population, gravitational focusing and that cloud interaction velocities are set by galactic shear and are larger (by about a factor of 2) than the local cloud velocity dispersion (see discussion in McKee & Ostriker 2007). Our derived collision timescales are also shorter than many estimates of GMC lifetimes (e.g., McKee & Williams 1997; Matzner 2002), which suggests that collisions are likely to be important even when feedback mechanisms are taken into account, i.e., an individual GMC is just as likely to have its properties dramatically altered by a merger than by a destructive mechanism such as supernova or ionization feedback.

The nearly constant ratio of $t_{\text{merger}}/t_{\text{orbit}}$ means that the cloud collision rate is tied to the global galactic dynamical timescale and, if cloud collisions are the trigger for the majority of star formation, then this provides a natural mechanism to explain the global SFR–gas content correlations observed by Kennicutt (1998) in which the overall star formation efficiency per galactic dynamical time is small, while having star formation occurs mostly on small scales at relatively high efficiency in a highly clustered mode (Tan 2000). The relation of star formation to cloud collisions in global galaxy simulations will be investigated in Paper II.

Figure 6. Top panel: evolution of volume-weighted PDF for gas density evaluated from 2.5 kpc $< r < 8.5$ kpc and $-1 < z < 1$ kpc. The jagged nature of the 0 Myr PDF is due to finite root grid resolution aliasing of the initial conditions, and does not influence the later evolution. Higher and lower density regions develop due to gravitational fragmentation. Note that there is relatively little evolution between 200 and 300 Myr. The volume fractions of GMCs (i.e., cells with $n_H > 100$ cm$^{-3}$ = $3.46 M_\odot$ pc$^{-3}$) at $t = 100$, 200, 300 Myr are (5.82, 4.28, 4.12) $\times 10^{-4}$, respectively. The smooth solid line is a log-normal fit to the portion of the PDF at cloud densities (see the text). Bottom panel: mass-weighted PDF for gas density evaluated over the same simulation volume. Again, these distributions show relatively little evolution between 200 and 300 Myr, and the GMC mass fractions at $t = 100$, 200, 300 Myr are $0.492, 0.688, 0.685$, respectively. (A color version of this figure is available in the online journal.)

The following caveats should be considered in the above estimates of the merger timescale. The simulated merger rate depends on the mass function and gravitational boundedness of the GMCs. More massive and more gravitationally bound GMCs will experience higher merger rates, although for typical cloud mass functions most of their collisions will be with lower-mass clouds. In Figure 9, we also show the merger timescale for clouds with $M_c \geq 10^6 M_\odot$, which is about a factor of 2
shorter than that of the average cloud. We will see below that the simulated GMC population mass function and gravitational boundedness are similar to observed values. The total number of clouds is not fully resolved in these simulations (the most common cloud mass is several $10^5 M_\odot$ in the high resolution run at late times). Higher resolution simulations are likely to resolve larger number of clouds, which would increase the merger rate, although not necessarily the total gas mass that has been compressed by collisional shocks. The inclusion of stellar feedback would likely lead to a reduced total mass fraction in clouds and a reduced gravitational boundedness of those clouds that do form, and these effects would reduce the merger rate.

4.2. GMC Properties with Simulation Time

The cloud mass function is shown in Figure 10(a). Since there is no star formation feedback in these models, it is difficult to destroy gravitationally bound gas clouds, except via their merger into more massive clouds or via disruptive collisions. Unbound and weakly bound clouds can also be destroyed by shearing tidal forces due to grazing and close cloud interactions. As a result, we expect the mean cloud mass to grow over the course of the simulation, and this behavior is seen in Figure 10(a). Note, however, that the peak of the cloud mass function is at $6 \times 10^5 M_\odot$ (for uniform binning in $\log M_c$) and this does not vary significantly from $t = 100$ to 300 Myr. Note the initial Toomre mass in a $Q = 1$ disk is $M_T \equiv \Sigma_g \lambda_J^2 \sigma_g^2 = 8.9 \times 10^6 (\sigma_g / 6 \text{ km s}^{-1})^2 (r / 200 \text{ km s}^{-1})^{-1} M_\odot$, about an order of magnitude larger than the peak of the simulated GMC mass function. The Jeans mass in the disk is $M_J = \pi \Sigma_g \lambda_J^2 \sigma_g^4 (G^2 \Sigma_g) \rightarrow 2.2 \times 10^6 (\sigma_g / 6 \text{ km s}^{-1})^2 (r / 200 \text{ km s}^{-1})^{-1} (Q / 1) M_\odot$, where $\lambda_J \equiv \sigma_g^2 / (G \Sigma_g)$ is the shortest wavelength permitting gravitational instability in a thin, nonrotating disk (Kim & Ostriker 2001). The gas tends to cool to the temperature floor of 300 K, for which $\sigma_g \approx 2 \text{ km s}^{-1}$ and thus $Q \approx 1/3$, resulting in $M_J \approx 3 \times 10^4 M_\odot$. The effect of simulation resolution on the cloud mass function at $t = 250$ Myr is shown in Figure 11(a). The number of GMCs appears reasonably well resolved down to masses of about $2 \times 10^6 M_\odot$.

The simulated cloud mass function can be compared to the observed mass spectrum of GMCs in the Milky Way and M33, which can be fitted by a power law $dN_c / (d \log M_c) \propto M_c^{-\alpha_c}$. In the Milky Way, $\alpha_c$ is observed to be $\approx 0.6$–$0.8$ (Williams & McKee 1997), whereas a steeper index of $\approx 1.6$ appears to hold in M33 (Rosolowsky et al. 2003). After collision and agglomeration processes have had enough time to operate, i.e. by $t = 200$ Myr, the shape of the simulated cloud mass function (in the mass range $\sim (0.5$–$10) \times 10^6 M_\odot$) is relevant to observations.

Figure 7. Density vs. temperature contour plots showing the distribution and evolution (100, 200, 300 Myr from left to right) of gas volume (top row) and mass (bottom row) in the galaxy disk for $2.3 \text{ kpc} < r < 8.5 \text{ kpc}$ and $1 \text{ kpc} < z < 1 \text{ kpc}$. The temperature floor of 300 K is evident: most “GMC” gas has this effective temperature, corresponding $\epsilon_c \approx 1.8 \text{ km s}^{-1}$. Lower temperatures are possible via adiabatic cooling. Most of the volume of the ISM exists at lower densities and higher temperatures, with different phases in approximate pressure equilibrium. In each panel, the solid lines show estimates of the total pressure in the Milky Way, $P_{\text{tot}} / k = 2.8 \times 10^4 \text{ K cm}^{-3}$ (top line), the total thermal pressure, $P_{\text{th}} / k = 0.36 \times 10^4 \text{ K cm}^{-3}$ (middle line), and the thermal pressure excluding the hot gas component, $P_{\text{th,cool}} / k = 0.14 \times 10^4 \text{ K cm}^{-3}$ (bottom line; Boulard & Cox 1990). Since our simulations do not yet include feedback (e.g., FUV heating, supernovae) or nonthermal pressure components (e.g., magnetic fields, cosmic rays), it is not surprising that our diffuse ISM pressure is 1–2 orders of magnitude smaller than the observed Milky Way value.

(A color version of this figure is available in the online journal.)
the more massive clouds. It remains to be determined whether these processes would still be as important for shaping the cloud mass function if stellar feedback processes were also operating, which would tend to reduce cloud lifetimes.

Williams & McKee (1997) also derived the normalization of the Galactic GMC mass function and noted there appears to be a truncation above a molecular mass of $M_c \approx 6 \times 10^5 M_\odot$ (see Equation (6)). Allowing for an equal amount of atomic gas associated with GMCs (Blitz 1990), this truncation would occur at $1.2 \times 10^7 M_\odot$. Williams & McKee (1997) estimate there are about $100$--$200$ inner Milky Way GMCs with $M_c > 10^6 M_\odot$, and about $1000$ with $M_c > 10^7 M_\odot$. If one allows for an equal mass of atomic gas associated with the observed molecular gas of these GMCs, then in comparison we find about $400$ clouds with $M_c > 2 \times 10^6 M_\odot$, a factor of $2$--$4$ higher than the Williams and McKee estimate. We do not adequately resolve the number of $2 \times 10^5 M_\odot$ clouds (Figure 11(a)) to make a useful comparison at that mass scale. These results may indicate that the number of massive GMCs in our simulation is a factor of a few larger than in the Milky Way. Indeed the mass fraction of gas in GMCs in the simulation is about $0.69$ (Figure 6), somewhat higher than the mass fraction implied by the analysis of Wolfire et al. (2003). Lack of feedback processes in the simulation is an obvious potential cause of this discrepancy. Another potential contributing factor is our somewhat arbitrary choice of $n_{H, c} = 100$ cm$^{-3}$ for the cloud threshold density. Note that M33, being a much smaller galaxy than the Milky Way, has fewer massive GMCs.

Figure 10(b) shows the average radius of the clouds defined as $R_{c,A} \equiv (A_c/\pi)^{1/2}$, where $A_c$ is the projected area of a cloud in the $y$--$z$ plane (i.e., as it would be observed by an observer embedded in the plane of the galaxy). The most common radius for a cloud is around $20$--$30$ pc (for uniform linear binning in $R_{c,A}$). By $300$ Myr, agglomeration processes have created a population of larger clouds. It is clear from Figures 10(a) and (b) that the numbers of these larger, more massive clouds are steadily increasing in time, and in this respect a steady state has not been reached. Such a steady state likely requires feedback processes. Nevertheless, the typical sizes of the cloud population are similar to observed sizes of GMCs in the Milky Way and other galaxies, such as M33 (Rosolowsky et al. 2003). The effect of simulation resolution on the distribution of cloud sizes is shown in Figure 11(b).

Figure 10(c) shows the distribution of mass surface density of the clouds, which is defined as $\Sigma_c \equiv M_c/A_c$. The peak of the distribution (for uniform binning in $\log M_c$) is at about $300 M_\odot$ pc$^{-2}$, and does not change significantly during the simulation. Although the number of more massive clouds is increasing, these are also larger, and so have similar values of $\Sigma_c$. Most clouds are within a factor of $3$ of this peak value. This surface density is similar to the mean value of $\sim 200 M_\odot$ pc$^{-2}$ derived by Solomon et al. (1987) from a $^{12}$CO
survey of the Galaxy. Heyer et al. (2008) have derived smaller values \(~100 \, M_\odot \, \text{pc}^{-2}\) based on better sampled $^{13}$CO surveys. To compare these observed values, which are based solely on molecular line (CO) emission, with our simulated clouds, one should also include their associated atomic gas, which may contribute at about the factor of 2 level. We conclude that,
even without disruptive effects of star formation feedback, our simulated GMCs attain values of $\Sigma_c$ that are similar to observed values. This may indicate that the dominant source of turbulent pressure support in GMCs is injected via cloud collisions and interactions (i.e., turbulent converging flows) rather than via star formation feedback. Note that Joung & Mac Low (2006) found that supernova-driven turbulence was insufficient to explain the observed ISM velocity dispersions. The effect of simulation resolution on the distribution of $\Sigma_c$ is shown in Figure 11(c): the peak of the distribution is relatively insensitive to resolution.

Figure 10(d) shows the distribution of GMC virial parameters (see Equation (7)), $\alpha_{\text{vir}} \equiv 5\sigma_c^2 R_{c,A}/(GM_c)$, where $\sigma_c$ is
the mass-averaged one-dimensional velocity dispersion of the cloud, i.e., $\sigma_c \equiv (c_s^2 + \sigma_{nt, c}^2)^{1/2}$, where $\sigma_{nt, c}$ is the one-dimensional rms velocity dispersion about the cloud’s center-of-mass velocity (Bertoldi & McKee 1992). A virial parameter of unity implies a spherical, uniform cloud with negligible surface pressure and magnetic fields is virialized, so that its total kinetic energy is half the magnitude of the gravitational energy. Surface pressure terms and a centrally concentrated density distribution tend to raise the value of $\alpha_{vir}$ corresponding to virial equilibrium (see Equation (7) and the discussion above). We see that the distribution of cloud virtual parameters peaks at $\alpha_{vir} < 1$, and decreases slightly as the simulation progresses: the peak of the virial parameter distribution at 300 Myr is about 0.6. This indicates that the clouds in the simulation are typically gravitationally bound, perhaps somewhat more strongly bound than observed GMCs, though there is still a significant population of unbound clouds. The effect of increasing simulation resolution on the distribution of $\alpha_{vir}$ is shown in Figure 11(d): the peak of the distribution moves to larger values and the fraction of unbound clouds grows.

Figure 10(e) shows the distribution of the vertical ($z$) component of specific angular momentum, $j_z$, of the clouds. The fraction of retrograde (i.e., $j_z < 0$) clouds grows at late times as clouds have had more opportunities to suffer mergers and close interactions (see also Dobbs 2008). The vertical line indicates the value of $j_z$ of a spherical ($\sim 110$ pc radius) region of the initial conditions at galactocentric radius $r = 4$ kpc containing $10^6 M_\odot$. (Kim et al. 2003 derive an analytic expression for $j_z \propto \Omega R_A^2 \Delta z$ for two-dimensional patches of galactic disks.) We see that GMCs typically have much smaller amounts of angular momentum compared to similar masses of diffuse gas that would be spread out over larger scales and be more susceptible to galactic differential rotation. The effect of simulation resolution on the distribution of $j_z$ is shown in Figure 11(e): at higher resolution it becomes more sharply peaked toward small value of $j_z$.

Figure 10(f) shows the distribution of cloud center-of-mass vertical positions relative to the disk midplane, i.e., where the vertical acceleration due to the galactic potential is zero. The rms heights of the cloud population at 100, 200, and 300 Myr are 13, 25, and 51 pc, respectively, growing at late times because of cloud–cloud gravitational scattering. Note that Stark & Lee (2005) derived a vertical scale height of Milky Way GMCs of $\lesssim 35$ pc. The effect of simulation resolution on the vertical distribution of clouds is shown in Figure 11(f).

Figure 12 shows the velocity dispersion versus size relation for clouds at $t = 250$ Myr. The effects of using the full velocity information to derive a mass-averaged one-dimensional internal velocity dispersion versus just using radial velocities at a particular viewing angle are examined. We also consider the effect of a mass cut, i.e., restricting the analysis only to the most massive clouds. Such effects are important in influencing the normalization and slope of the line-width size relation. Our simulated cloud population has a similar, though somewhat higher, velocity dispersion versus size relation to observed GMCs, such as those observed in M33 by Rosolowsky et al.
Figure 13. Distribution of the angle, $\theta$, between cloud angular momentum vectors and the galactic rotation axis at different times during the course of the simulation. The shaded bars indicated retrograde rotation, and this population grows with time as more and more clouds experience collisions and close interactions.

Figure 14. Distribution of the position angle, $\theta'$, of cloud angular momentum vectors with respect to the galactic rotation axis as determined from radial velocities for $t = 250$ Myr, for which the retrograde fraction of $\theta$ is 0.28, and for inclination angles of 0° (relevant to edge on disks including the Milky Way), 30°, 45°, 52° (relevant to M33), 60°, and 90°. The black line shows the observational results from Rosolowsky et al. (2003) for 45 clouds in M33 of which 18 are retrograde (as defined by $\theta'$).

(2003), in the Milky Way by Solomon et al. (1987), or the average of a number of extragalactic systems, $\sigma_c = \sigma_{pc}(R/pc)^{\alpha_\sigma}$ with $\alpha_\sigma = 0.60 \pm 0.10$ and $\sigma_{pc} = 0.44 \pm 0.15$ km s$^{-1}$, derived by Bolatto et al. (2008). The larger velocity dispersion of the simulated clouds at a given size scale may be due to the lack of star formation feedback causing them to be more tightly gravitationally bound than real clouds. A discrepancy may also result due to differences in how the effective radius of clouds is evaluated for the simulation clouds and the real clouds. The dispersion of the simulated clouds about the best-fit relation is about 2.2 km s$^{-1}$ (for the sample in the lower-right panel of Figure 12), corresponding to about 40% of $\sigma_c$. Solomon et al. (1987) found a dispersion of about 30% in their sample of Galactic GMCs (see also Heyer & Brunt 2004).

Figure 13 shows the distribution of the angle, $\theta$, between the cloud angular momentum vector and the galactic rotation axis at different times in the simulation. At early times, in the initial fragmentation phase clouds are all born with prograde rotation ($0^\circ < \theta < 90^\circ$), i.e., in the same sense as the galactic rotation. At later times, cloud interactions lead to a build up of a retrograde ($90^\circ < \theta < 180^\circ$) cloud population, which is about 30% of the total.

To compare to observed systems, one needs to account for the viewing angle to the galaxy and the fact that only line-of-sight velocities are used to determine rotation. Figure 14 shows these effects by plotting the distribution of position angles, $\theta'$, of cloud rotation axes derived from radial velocities along sight lines at different inclination angles to the simulated galaxy at $t = 250$ Myr, when the retrograde fraction of $\theta$ is 0.28. These results indicate that the derived retrograde fraction depends on inclination angle: e.g., for the 0° (edge on) case the retrograde fraction inferred from $\theta'$ is about twice that as measured by the actual angular distribution of $\theta$. The figure also shows the observational results of Rosolowsky et al. (2003), who find about 40% (18 out of 45) of the GMCs in M33 have apparently retrograde rotation. Their results are broadly consistent with our simulation results (note their slightly larger bin size), but we emphasize that we can only make a qualitative comparison at this stage, since our model galaxy was not set up to mimic the details of M33 (e.g., its rotation curve), nor does it yet include
Figure 15. Normalized distributions of GMC properties, as described in Figure 10, but now showing results for different cloud ages: 0–1 Myr (solid lines), 9–10 Myr (dashed lines), 49–50 Myr (dot-dashed lines), 99–100 Myr (dotted lines), for those clouds born after \( t = 140 \) Myr, i.e., in the fully fragmented phase. Top left: (a) cloud mass, \( M_c \). Middle left: (b) cloud radius, \( R_{c,A} \equiv (A_c/\pi)^{1/2} \). Bottom left: (c) mass surface density, \( \Sigma_c = M_c/A_c \). Top right: (d) virial parameter, \( \alpha_{\text{vir}} \). Middle right: (e) vertical (\( z \)) component of specific angular momentum, \( j_z \). Bottom right: (f) cloud center-of-mass vertical positions, \( z \).

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

the effects of stellar feedback. Nevertheless cloud formation in a self-gravitating, shearing disk and cloud evolution via cloud–cloud interactions appear to be promising mechanisms to help explain the observed angular distributions of cloud angular momentum vector orientations.

4.3. GMC Properties with Cloud Age

Our method of tracking clouds from one output time to the next allows us to study the evolution of cloud properties as a function of cloud age, \( t' \). Figure 15, analogous to Figure 10, shows how the distribution of cloud masses, radii, mass surface densities, virial parameters, vertical component of specific angular momentum, and vertical positions changes with cloud age \( (t' = 0–1, 9–10, 49–50, 99–100 \) Myr) for clouds born after \( t = 140 \) Myr, i.e., in the fully fragmented phase of the simulation. Younger, especially newly formed, clouds tend to have lower masses, slightly smaller radii, lower mass surface densities, and larger virial parameters (i.e., are less gravitationally bound). However, young clouds have very similar distributions
of the vertical component of specific angular momentum and of vertical position above and below the disk midplane.

Figure 16 shows the distribution of the angles, $\theta$, between cloud angular momentum vectors and the galactic rotation axis for different cloud ages for clouds born after $t = 140$ Myr in the fully fragmented stage. The fraction of retrograde clouds is about 25% of the total and nearly independent of cloud age. The latter processes occur very frequently: a cloud typically suffers a merger every 1/5 of an orbital time, i.e., about every 25 Myr at $r = 4$ kpc. GMC mergers and collisions, which can be viewed as being somewhat equivalent to turbulent converging flows in a self-gravitating and shearing gas disk, are thus efficient at injecting kinetic energy into the clouds (extracted from orbital energy) and maintaining near virial balance of the clouds. This mechanism may be as important as, or even more important than, stellar feedback, such as momentum injection by supernovae, stellar winds, or ionization, at keeping GMCs turbulent. A comparison of these processes will be studied in a future paper.

Cloud collisions may also be efficient triggers for star formation, since they cause dense gas that is already somewhat prone to star formation to be pressurized by the ram pressure of the converging clouds. This could push magnetically subcritical clumps inside GMCs to become supercritical, thus triggering star cluster formation. Our result that the cloud collision time is a small and approximately constant fraction of the local orbital time, lends support to theory of cloud collision induced star formation to explain the global Kennicutt (1998) star formation relations, as proposed by Tan (2000). The correlation of star formation activity with cloud collisions will be investigated in Paper II.

The complexity of the star formation process means that theoretical models and numerical simulations must be closely tested against observed systems. An important future goal is to test how GMC properties and star formation activity depend on global galactic properties such as rotation curve shape and velocity normalization, strength of spiral arm potential, and gas metallicity. Our results presented here provide a foundation for these future studies.

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5. CONCLUSIONS

We have presented simulations of GMC formation and evolution in a marginally unstable gas disk of a flat rotation curve galaxy, capturing scales from $\sim 20$ kpc down to $\lesssim 10$ pc, with a fully multiphase atomic ISM. In this initial study, we have focused on the limit of a negligible SFR from the gas and negligible feedback from those stars. We imposed a minimum effective sound speed of 1.8 km s$^{-1}$ to mimic nonthermal forms of pressure support in the dense gas. We did not explicitly track molecule formation on dust grains, but rather defined GMCS to be those structures with $n_H \gtrsim 100$ cm$^{-3}$, similar to the mean volume-averaged densities of observed GMCs. Using AMR we resolved fragmentation of gas up to densities of about this cloud threshold density. We developed methods to track clouds through the simulation, including mergers.

In spite of the simplicity of the model, a surprisingly large number of observed GMC properties are approximately reproduced by the simulated cloud population at late simulation times, $t > 140$ Myr, once the disk is fully fragmented. These include the distributions of cloud mass, size, mass surface density, virial parameter, angular momentum, vertical height in the disk, linewidth size relation, and distribution of angles of angular momentum vectors with respect to the galactic rotation axis. Many of the ISM and cloud population properties approach a quasi-steady-state at late simulation times, indicating an approximate balance between gravitational instability, heating of the cloud velocity dispersion via gravitational scattering (and perhaps some numerical diffusion) and dissipation via cloud collisions and mergers. The fraction of retrograde clouds is about 25% of the total and nearly independent of cloud age.
