RAPID MOLECULAR CLOUD AND STAR FORMATION: MECHANISMS AND MOVIES

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ABSTRACT

We demonstrate that the observationally inferred rapid onset of star formation after parental molecular clouds have assembled can be achieved by flow-driven cloud formation of atomic gas, using our previous three-dimensional numerical simulations. We postprocess these simulations to approximate CO formation, which allows us to investigate the times at which CO becomes abundant relative to the onset of cloud collapse. We find that global gravity in a finite cloud has two crucial effects on cloud evolution. (1) Lateral collapse (perpendicular to the flows sweeping up the cloud) leads to rapidly increasing column densities above the accumulation from the one-dimensional flow. This in turn allows fast formation of CO, allowing the molecular cloud to “appear” rapidly. (2) Global gravity is required to drive the dense gas to the high pressures necessary to form solar-mass cores, in support of recent analytical models of cloud fragmentation. While the clouds still appear “supersonically turbulent,” this turbulence is relegated to playing a secondary role, in that it is to some extent a consequence of gravitational forces.

Subject headings: gravitation — instabilities — ISM: clouds — stars: formation — turbulence

1. INTRODUCTION

One motivation for pursuing a picture of molecular cloud formation by large-scale flows was to resolve the “crossing time problem,” i.e., the fact that the age spreads of young stars are often much shorter than lateral dynamical timescales (Ballesteros-Paredes et al. 1999; Hartmann et al. 2001, hereafter HBB01). In this picture, dense star-forming clouds are produced as flows—expanding H II regions, stellar wind bubbles, supernova explosions, spiral density waves (e.g., Bonnell et al. 2006), or global gravitational instabilities (e.g., Yang et al. 2007)—sweep up and condense diffuse interstellar gas. The crossing time problem is eliminated because information is not being transmitted along the long dimension of the cloud.

A major attraction of the notion of flow-driven molecular cloud formation is that we see several examples of it in the solar neighborhood, such as in Cep OB2 (Patel et al. 1998), in addition to the well-known cloud and star formation in galactic spiral arms due to gas inflow (e.g., Elmegreen 1979, 2007; see, e.g., Kim et al. [2003] and Dobbs & Bonnell [2007b] for numerical evidence). While it is not always easy to identify specific driving sources in all cases, this is not surprising given the complexity expected as a result of the interaction of neighboring flows. In addition, the presence of molecular clouds well out of the Galactic plane (e.g., Orion) clearly suggests the need for some kind of driving. Given the extensive impact that massive stars have on the interstellar medium—H II regions, stellar wind impacts, and ultimately supernova explosions—it is difficult to see how further creation of new star-forming locales by flows with scales of several to tens of parsecs (or even kiloparsecs, in the case of spiral arms) could be avoided.

Star-forming clouds in this picture become somewhat accidental associations of gas which are not in virial equilibrium, although rough energy equipartition is expected (HBB01), in adequate agreement with observations (Ballesteros-Paredes 2006). Indeed, it is very difficult to prevent global gravitational collapse motions in finite clouds of many Jeans masses (Burkert & Hartmann 2004), consistent with the empirical evidence for rapid star formation following cloud formation (HBB01).

While global gravitational contraction provides a plausible mechanism for assembling protocluster gas and stars and even overall cloud morphology (Hartmann & Burkert 2007), it poses difficulties for local collapse; nonlinear perturbations are probably required to avoid sweep-up in overall collapse modes (Burkert & Hartmann 2004). The necessity of producing star-forming clumps through turbulent motions has long been recognized (Larson 1981), based on a large number of numerical simulations over the years (see review by Mac Low & Klessen 2004). However, the source of this turbulence has been a matter of debate. The flow-driven cloud formation picture may provide an answer, in that the dynamical instabilities coupled with rapid cooling and thermal instability which naturally result at the shock interface between driving material and swept-up gas generate turbulence and nonlinear density fluctuations (Koyama & Inutsuka 2002; Inutsuka & Koyama 2002; Audit & Hennebelle 2005; Heitsch et al. 2005, 2006b, 2008b; Vázquez-Semadeni et al. 2006, 2007; Hennebelle et al. 2007, 2008; Hennebelle & Audit 2007). Based on a consideration of timescales, Heitsch et al. (2008a) demonstrate that these instabilities do indeed proceed much faster than global gravity, as required.

As simulations of the relevant processes become more detailed, we are increasingly in a position to test the implications of flow-driven molecular cloud and star formation. In this paper we analyze numerical models published elsewhere (Heitsch et al. 2008b, hereafter H08b) to illustrate some general predictions of the flow-driven picture, and help clarify some confusing issues about molecular cloud and star formation region lifetimes.

2. MODELS

2.1. Overview

The interstellar medium is filled with flows of various types, many of which result in piling up material through shocks. Recognition of this fact is at the heart of the flow-driven cloud formation picture. While many different types of initial conditions can be envisaged—flows driven by hot gas expansion (H II regions, supernova bubbles), flows within mostly molecular gas—we focus
on the particular case of mildly supersonic flows in atomic gas. We do this for two reasons: first, it is computationally simplest for our present situation; and second, it should be representative of conditions in the solar neighborhood, where most of the gas is atomic (or ionized) and only a modest fraction in mass and a very modest fraction in volume is present as molecular gas. We expect that many of the qualitative and even semiquantitative results will apply to other situations, although that needs further exploration.

We also chose to have equal uniform flows entering on either side of our computational volume. This is obviously not the most general case. However, we have run some models in which differing density atomic flows collide; this amounts to transforming into the frame of the shock front of an expanding bubble (for example). The results of these cases do not differ substantially from the results we present here, and so we confine the discussion to the simplest possible cases.

We also chose to have smooth inflows and introduce only a modest perturbation of their initial interface. We did this not out of the absolute conviction that the flows themselves are not turbulent, but with the desire of introducing as little substructure by hand as possible. By showing that even relatively smooth conditions rapidly introduce turbulence, we can show that any other initial substructure will merely add additional structure to our clouds.

Finally, we chose not to use periodic boundary conditions. This has absolutely crucial effects on the gravitational accelerations within the forming cloud. Global, gravitationally driven flows play important roles in cloud evolution, and these cannot be seen in models with periodic boundary conditions.

By addressing the formation processes of a cloud, we are able to examine the initial conditions which lead to structures and velocity fields important for star formation.

2.2. Model Set

We base our analysis and discussion on the models introduced in H08b. They describe the flow-driven formation of an isolated cloud with the parameters given in Table 1. All models are run on a fixed grid with the instreaming gas flowing along the x-direction, entering the domain (in opposing directions) at the two (y, z)-planes. The nominal resolution (i.e., the size of a single grid cell) is \(8.6 \times 10^{-2}\) pc. To trigger the fragmentation of the (otherwise plane-parallel) region of interaction, we perturb the collision interface. We chose the perturbations of the collision interface from a random distribution of amplitudes in Fourier space with a top-hat distribution restricted between wavenumbers \(k = 1\) and 4.

The inflow is restricted to a cylinder of elliptical cross section with an ellipticity of 3.3 and a major axis of 80% of the (transverse) box size, mimicking two colliding gas streams in a more general geometry. Model Hf1 is a nongravitating version of Gf1, to compare the role of gravity versus that of the thermal instability for the fragmentation of the gas streams.

The inflow density in all models is \(n_i = 3\) cm\(^{-3}\) at a temperature of \(T_i = 1800\) K and an inflow velocity of \(v_i = 7.9\) km s\(^{-1}\), corresponding to a Mach number of \(M = 1.5\). The flows are initially in thermal equilibrium. The models start at time \(t = 0\) with the collision of the two flows. The fluid is at rest everywhere except in the colliding cylinders.

To solve the hydrodynamical equations, we used the higher order gas-kinetic grid method Proteus (Prendergast & Xu 1993; Slyz & Prendergast 1999; Heitsch et al. 2004, 2006b, 2007; Slyz et al. 2005). The code evolves the Navier-Stokes equations in their conservative form to second order in time and space. The hydrodynamical quantities are updated in time-unsplit form.

Self-gravity is implemented as an external source term, also in time-unsplit form. The Poisson equation is solved via a non-periodic Fourier solver, using the (MPI parallelized) FFTW (Fastest Fourier Transform in the West) libraries. The heating and cooling rates are restricted to optically thin atomic lines following Wolfire et al. (1995). Numerically, heating and cooling is implemented iteratively as a source term for the internal energy. While we do not include molecular line cooling, the resulting effective equation of state reproduces the quasi-isothermal behavior expected at high densities, reaching a temperature of \(\approx 14\) K at densities of \(\approx 10^5\) cm\(^{-3}\).

The x-boundaries are partly defined as inflow boundaries. The inflow is defined within an elliptical surface in the (y, z)-plane. The y- and z-boundaries—as well as the part of the x-boundaries that is not occupied by the inflow—are open, meaning material is free to leave the simulation domain through these boundaries. For a detailed discussion of the numerical scheme and the models, see H08b.

In view of the more general situation, we explored a variety of geometries and flow parameters, such as expanding shells, unrestricted inflows, and flows with different densities, the latter probably being the most general scenario for, e.g., swept-up clouds at the rims of supernova bubbles. Despite the variations, the basic mechanisms and results do not change substantially. Specifically, the combination of thermal and dynamical instabilities enhances local gravitational collapse in all cases.

2.3. CO Formation

Our models do not explicitly follow the transition from atomic to molecular gas. However, conditions in the dense postshock gas should result in molecule formation at some point (see Glover & Mac Low [2007a, 2007b] for a discussion of \(\text{H}_2\) formation in turbulent flows). To illustrate what would be observed as a molecular (CO) cloud we make a simple approximation, motivated by the notion that CO formation requires shielding by dust grains. For each time instance shown in § 3, we decide whether CO is “present” in a particular grid cell by determining the expected radiation field integrated over solid angles. If the effective UV extinction is equivalent to that of an angle-averaged \(A_V = 1\) and the local temperature is \(T < 50\) K, we assume CO is present in high abundance. Because CO is rapidly dissociated at lower extinctions (van Dishoeck & Black 1988), we do not advect CO for simplicity. The radiation field at each grid point is calculated by measuring the incident radiation for a given number of rays and averaging over the resulting sky. The ray number is determined such that at a radius corresponding to half the box size, each resolution element is hit by one ray. Thus, fine structures and strong density variations are resolved (see also Heitsch et al. 2006a). Since our CO maps are postprocessed maps, there is no timescale of CO formation involved, but CO is assumed to

### Table 1: Model Parameters

| Name     | \(L_x L_y L_z\) (pc) | Gravity | \(t_{\text{end}}\) (Myr) | \(\eta\) (pc) |
|----------|----------------------|---------|------------------------|-------------|
| Hf1      | 256 \(\times 512^2\) 22 \(\times 44^2\) No 14.5 2.2 |
| Gf1      | 256 \(\times 512^2\) 22 \(\times 44^2\) Yes 14.5 2.2 |
| Gf2      | 256 \(\times 512^2\) 22 \(\times 44^2\) Yes 14.5 4.4 |

Notes.—Col. (1): Model name. Col. (2): Resolution. Col. (3): Physical grid size. Col. (4): Gravity. Col. (5): End time of run. Col. (6): Amplitude of interface displacement.
appear instantaneously in sufficiently shielded regions. This simplification leads to “more” CO being present, countering the neglect of advected CO. A full treatment of CO formation including (even a simplified) chemical network (e.g., Bergin et al. 2004), advection of chemical species, and consistent radiative transfer would be a major computational challenge and beyond the degree of detail necessary for our argument. The issue of CO formation is discussed further in § 4.1.

We concentrate on CO rather than on H₂ formation because CO is the first available tracer to indicate the appearance of a molecular cloud, whereas H₂ is usually not directly observable in clouds. As Figures 1 and 3 of Bergin et al. (2004) show, H₂ formation sets in well before CO formation due to self-shielding instead of dust shielding—specifically if traces of H₂ are already present in the swept-up material (e.g., Pringle et al. 2001).

3. AT THE MOVIES

We now proceed to look at the evolution of the forming cloud with our crude treatment of CO formation. For reference, note that in the absence of any substructure or collapse, the column density along the x-axis would vary with time as

\[
\langle N_H \rangle = 2 \times 7.9 \text{ km s}^{-1} \times 3 \text{ cm}^{-3} t = 1.5 \times 10^{20} \text{ cm}^{-2}(t/\text{Myr}),
\]

and the mass of the cloud would be

\[
M_c \sim 500 M_\odot(t/\text{Myr}),
\]

using the approximate area of our model cloud. Thus, at the end of the three simulations (\(t = 14.5\) Myr), the average column density through the cloud in the absence of substructure would be \(N_H \sim 2.2 \times 10^{21} \text{ cm}^{-2}\) or \(A_V \sim 1.1\), and the cloud mass \(M_c \sim 7500 M_\odot\). The actual molecular mass of the cloud will be smaller than this (see below), so our simulation is related to the formation of a small molecular cloud.

3.1. Cloud Formation and Onset of Star Formation

Figures 1 and 2 provide snapshots of the cloud evolution at various times in the form of column density maps, where we use contours to illustrate H i levels at levels of \(\log N_{H_1} = 20, 21, 22\), with colors showing those hydrogen column densities at which CO is “strongly present.” Figure 1 shows the cloud formation seen along the inflows, and Figure 2 gives an “edge-on” view.

While at early times the small-scale structure in the H i column densities indicates the rapid fragmentation of the inflows due to thermal and dynamical instabilities in all three cases, the subsequent evolution is very different. Consider first the leftmost columns in Figure 1, which illustrates the evolution of model Hf1, in which gravity has been turned off, seen along the direction of the flows. Very little CO formation occurs over the \(\sim 15\) Myr buildup of material. The resulting “cloudlets” are small, relatively thin (\(A_V \approx 1\)), and in some cases transient, due to the continuing input of turbulent energy from the inflows.

Things are dramatically different for the evolutionary sequence Gf1 in the center column of Figure 1, where gravity is present at all times. Although there is little change in behavior at \(t = 5.3\) Myr, by \(t = 7.6\) Myr Gf1 has significantly more “CO,” although the concentrations are not strongly self-gravitating (§ 4.2). By \(t = 9.9\) Myr the model with gravity has formed a broken ring.

This structure results from the “edge effect” of nonlinear gravitational acceleration in a finite cloud (Burkert & Hartmann 2004; H08b); it is in some sense an “echo” of the initial cloud boundary. The slightly more compressed appearance of the H i contours (see also Fig. 2 of H08b) indicates that it is the global gravitational modes and the resulting lateral collapse motions (perpendicular to the inflow) which increase the local column density. The peak column densities at 10 Myr are above \(10^{22} \text{ cm}^{-2}\), compared to the average value \(\sim 1.5 \times 10^{21} \text{ cm}^{-2}\) expected at that time. Overall, the rapid production of shielded molecular gas is strongly enhanced by lateral gravitational collapse or sweep-up of gas, an effect initially suggested by Bergin et al. (2004; see § 4.2). The lateral collapse overcomes the perceived limitations of the flow-driven cloud formation scenario that within reasonable timescales the column densities would be too low for efficient molecule formation (e.g., McKee & Ostriker 2007). This can also be seen in Figure 3, which shows the density-weighted width of clouds Hf1 and Gf1 along their short axis against time. At around 8 Myr, the widths start to separate, indicating the global gravity effects. The effect in the widths is somewhat lessened by the edge effect due to the nonlinear gravitational accelerations, which nevertheless help sweeping up material laterally and thus increasing the shielding. By \(t = 12.2\) Myr (Fig. 1) several local small condensations appear which are very dense and strongly self-gravitating. The overall region continues to collapse laterally under gravity until it forms something close to a single filament at \(t = 14.5\) Myr.

The evolution of model Gf2 in the right-hand column is fairly similar to that of Gf1. The larger physical perturbations result in somewhat denser concentrations of gas by \(t = 9.9\) Myr, and the overall collapse tends to produce a single narrow filament by the end of the simulation.

Figure 2 shows column densities in a side view of the three simulations. The main concentrations formed in models Gf1 and Gf2 are driven initially at the positions of inflections in the initial perturbed interface by dynamical focusing (Hueckstaedt 2003; H08b) due to the nonlinear thin shell instability (Vishniac 1994). These views show that the resulting clouds and dense concentrations are far from spherical or even spheroidal, but quite elongated and, eventually, strongly filamentary.

Once column densities of \(N \approx 10^{22} \text{ cm}^{-2}\) have been reached (at \(\approx 10\) Myr), gravitationally dominated cores start to form (symbols in Fig. 4). Cores are identified by a modified version of CLUMPFIND (Williams et al. 1994; Klessen et al. 2000), with the additional condition that the thermal plus kinetic energy content is less than half of the gravitational potential energy (see H08b). This is consistent, for example, with the results of Onishi et al. (1998), who studied cores in Taurus with C18O and found a column density threshold for star formation of about \(8 \times 10^{21} \text{ cm}^{-2}\).

We cannot follow the collapse of these dense regions to anything approaching the sizes of stars. However, it is instructive to consider not only whether the regions are self-gravitating but also the timescales on which they might collapse. Figure 5 shows the distribution of mass as a function of its local free-fall timescale, binned linearly for the top row and logarithmically for the bottom row for clarity. The bulk of the mass in the simulation domain remains at long free-fall times. The formation of the first gravitationally bound cores occurs in the simulations with gravity at about 10 Myr, as shown in Figure 4; at about the same time, a small amount of mass exhibits free-fall timescales of order 1 Myr or so. It is only at \(t \sim 11–12\) Myr that appreciable amounts of mass are present with free-fall timescales of \(< 1\) Myr,
thus, we estimate that this is the epoch at which star formation begins. It is evident, given the increase in the number of self-gravitating cores and the decrease in free-fall times, that star formation in this model would be an increasing function of time to the end of the simulation.

4. DISCUSSION

4.1. What Would We Observe?

The cloud evolution that we have presented obviously takes far too long to be observable. For purposes of comparison with
observation one can think in terms of observing four different clouds, each having the same evolution, but studied at different epochs. We also compare at each stage with some observed clouds of similar properties, with the primary goal of checking whether our prescription for CO formation appears reasonable, either with respect to observations or to theoretical treatments for these clouds. We restrict attention to model Gf1 initially.

"Cloud 1" (the top row of Fig. 1) would be difficult to detect in molecular gas emission, but could be inferred through absorption-line studies and extinction, especially in the small
blobs. This object would be classified as a diffuse \(\text{H} \, \text{I} \) cloud with a visual extinction \(A_V \sim 0.4\).

“Cloud 2” (second row), with an age of 7.6 Myr, would still be classified as a diffuse \(\text{H} \, \text{I} \) cloud. It has a small amount of CO, mostly in localized positions; Figure 4 demonstrates that very little of the cloud is CO-bearing at this phase. The average extinction through the cloud would be \(A_V \sim 0.6\), with of course some localized higher column density regions; such properties are roughly consistent with local lines of sight to, for example, \(\zeta \text{ Oph} \) and \(\zeta \text{ Per} \), for which van Dishoeck & Black’s (1988) models are consistent with the presence of small amounts of CO.

Here we should emphasize that our prescription for CO formation relies heavily on results such as those of Figure 5a of van Dishoeck & Black (1988), which indicate photodissociation timescales \(>1 \text{ Myr}\) for \(A_V \gtrsim 1\). Their analysis implies the presence of substantial amounts of \(\text{H}_2\)—roughly comparable to the amount of \(\text{H}\) in the \(\zeta \text{ Per} \) and \(\zeta \text{ Oph} \) lines of sight. However, our models would not form any significant amounts of \(\text{H}_2\) at the stage of “Cloud 2,” because essentially none of the gas is at densities high enough to form molecular hydrogen rapidly enough (Bergin et al. 2004; formation timescales \(>1 \text{ Myr}\) at densities \(<10^7 \text{ cm}^{-3}\), corresponding to local free-fall timescales \(>1 \text{ Myr}\); see Fig. 5). The only way that there would be significant amounts of \(\text{H}_2\) present at this time (or in “Cloud 2”) is if it were present in the inflowing gas (e.g., Pringle et al. 2001). Thus, if anything we may have overestimated the amount of CO present at this stage.

“Cloud 3” (third row) now begins to show significant amounts of CO. According to Figure 4, the mass in CO is now about 500 \(M_\odot\) in the small-perturbation model Gf1 and about \(10^3 M_\odot\) in the large-perturbation model Gf2. However, no self-gravitating cores have formed at this point.

One might regard “Cloud 3” as an example of the most massive of the so-called translucent clouds, which are generally observed at high Galactic latitude (e.g., Magnani et al. 1985, 1996; Yamamoto et al. 2003). The constraint on Galactic latitude probably represents an observational selection effect rather than a complete absence of such objects in the Galactic plane. Observationally, star formation is rare or absent in this type of cloud, consistent with our simulations. For example, in their study of the \(\text{H} \, \text{I} \) filament associated with the molecular complex including MBM 53, 54, and 55, which has a mass of about 1200 \(M_\odot\) and a length of about 30 pc (assuming a distance of 150 pc), Yamamoto et al. (2003) found no evidence for any star-forming cores, although there is evidence for one or two young weak-emission \(T\) Tauri stars in the region. Note also that translucent clouds are known to have variations in CO abundances of an order of magnitude, even for various positions within the same cloud (Magnani et al. 1998 and references therein), which of course is what would be expected for a turbulent, structured translucent cloud like “Cloud 3.”

“Cloud 4,” which appears at \(t \sim 12 \text{ Myr}\), is now a molecular cloud, with a mass associated with CO of order 1200 \(M_\odot\). It now contains a small but significant amount of mass which is both gravitationally bound and is at densities corresponding to free-fall timescales less than 1 Myr; thus, we consider that it has now begun to form (low mass) stars.

Finally, “Cloud 5” is now a full-fledged molecular cloud, with a mass associated with CO of order 2500 \(M_\odot\) and dense cores comprising of order at most 25% of the mass associated with CO and of order 5% of the total mass of the cloud including \(\text{H} \, \text{I} \). The cores are contained within a strongly confined region spatially, due to the global gravitational collapse of the material.

The behavior of model Gf2, with a larger initial perturbation, is very similar, except that high densities are achieved a little earlier, the cloud collapses into a better defined filament, and the efficiency of massive core/star formation is larger (Fig. 4). Note that the fraction of mass in gravitationally bound regions does not directly correspond to the rate of star formation. For example, in model Gf2 at the end of the simulation there is about 2000 \(M_\odot\) in gas containing CO, but only \(<10^5 M_\odot\) of this material is actually contained in regions with free-fall times of 1 Myr or less (Fig. 5). Thus, in all cases we expect star formation efficiencies would be of order a few percent at most, by the end of the simulations.

The sizes and masses of models Gf1 and Gf2 at the final, “Cloud 4” stage are reasonably consistent with those of one of the major filaments in the Taurus molecular cloud (Hartmann 2002). One may even take this a step further and argue that star (core) formation could have only started in these models at times \(\sim 11–12 \text{ Myr}\), so that at 14.5 Myr the age spread is only of order 2–3 Myr, again reasonably consistent with that of Taurus (Hartmann 2003); but one would then need to shut off star formation to maintain the agreement with observation (§ 4.6).
The above sequence of “clouds” is not meant to suggest that all low-mass atomic clouds will eventually become molecular, star-forming regions. In particular, high-latitude clouds may well remain atomic, simply because they cannot sweep up enough mass.

4.2. Rapid Molecular Cloud Formation

The simulation sequences shown in Figures 1 and 2 support previous suggestions of rapid cloud and star formation. Specifically, HBB01 argued that the paucity of substantial molecular clouds without star formation meant that collapse of molecular cloud cores must follow soon after cloud formation. They further suggested that this was the result of the required shielding column density for molecular gas against the dissociating interstellar radiation field, which was similar to that needed for gravitational collapse. Our simulations demonstrate this behavior, with molecular (CO) gas setting in near core formation. The bulk of the mass stays at free-fall times longer than the simulation time. At 10 Myr, a few 100 $M_\odot$ have reached free-fall times $\tau_f < 1$ Myr, indicating local gravitational collapse. Even when logarithmically binned, the mass at small free-fall times is sufficient to form stars.

$$\rho \sim \rho_i v_i^2 (k_b T / \mu m_\text{H})^{-1},$$

where $\rho_i$ and $v_i$ are the inflow density and velocity, respectively, and $T$ is the temperature. In terms of densities and velocities $\bar{\rho}_i$ and $\bar{v}_i$ relative to the values used in these simulations ($v_i = 7.9$ km s$^{-1}$ and $n_i = 3$ cm$^{-1}$; see § 2.2),

$$n \sim 750 T_{30}^{-1} \bar{\rho}_i \bar{v}_i^2 \text{ cm}^{-3},$$

or

$$\tau_f = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \sim 1.9 T_{30}^{1/2} \bar{\rho}_i^{-1/2} \bar{v}_i^{-1} \text{ Myr.}$$

This estimate is in reasonable agreement with Figure 5, which shows a substantial amount of gas at $\tau_f \sim 2$ Myr, with higher temperature material at $\tau_f \sim 6$ Myr. Thus, simply due to ram pressure, moderately cold gas in the cloud is formed at densities such that free-fall timescales are short. This allows rapid gravitational collapse once sufficient mass has been accumulated.

Another feature of our model is that, as Bergin et al. (2004) showed using a one-dimensional shock model with chemistry, much of the time spent accumulating cloud mass is spent in the atomic phase; such clouds would not be recognized as “proto” molecular clouds. Beyond this, however, local gravitational collapse tends to occur with CO formation because global gravitational collapse is responsible for accelerating the formation of high column density, highly shielded gas which can become molecular. This was already foreseen by Bergin et al., who suggested that lateral collapse under gravity would be responsible for producing “runaway” increases in column density, enhancing the rate of molecule formation beyond what can be achieved in a one-dimensional flow. We observe precisely that behavior in our cloud sequence in Figures 1 and 2 (compare the left-hand column without gravity to the center and right-hand columns with gravity). Dobbs et al. (2008) discuss the formation of $H_2$ clouds in spiral arms and argue that substantial fractions of $H_2$ can be formed rapidly even without self-gravity. This does not
Burkert & Hartmann (2004) also demonstrated that finite sheets experience highly nonlinear gravitational acceleration as a function of position which tends to cause material to pile up near cloud edges. Our simulations confirm this; even though the resulting clouds are three-dimensional instead of being sheets, they are flat enough that the initial elliptical boundary is echoed in the resulting filamentary collapse (an even stronger version of the edge effect is present in Vázquez-Semadeni et al. [2007], whereas we took steps to suppress the strength of the edge effect by reducing the inflow mass addition near the boundaries).

To summarize, reasonable ram pressures of inflowing material result in cold atomic gas with densities sufficiently large that gravitational collapse can be rapid once sufficient material is accumulated. Substantial turbulent fragmentation is needed to form stellar-mass objects. Global collapse is generally important in driving up column densities and enhancing the formation of filamentary structures through edge effects. Free-fall times, Jeans masses, and lengths will decrease, and global collapse will occur faster for higher inflow rates and ram pressures, which probably are needed to make more massive clouds than those of our simulations.

We emphasize that simulations with periodic boundary conditions cannot capture the evolution seen here, in particular the rapid increase in column density within filamentary structure. Simulations with periodic gravity can only be relevant if started with substantial perturbations, and limited to scales much smaller than the overall sizes of clouds.

4.3. “Accelerated” Star Formation

Palla & Stahler (2000, 2002) estimated ages for stars in several local star-forming regions, finding that the rate of star formation generally showed an increase up to the last 1 Myr or so. As Hartmann (2002, 2003) pointed out, it is implausible that all of these star-forming regions should be coordinated in their evolution; it must be that the typical lifetimes of star-forming regions are at most a few megayears. Hartmann (2002, 2003) also pointed out some problems related to neglect of observational errors, logarithmic versus linear binning in age, and likely isochrone or birth line problems which exaggerate the age spreads of these regions. Nevertheless, there is evidence that a small fraction of the stars associated with these areas are a few megayears older than the bulk of the population.

Accelerated star formation is expected in a trivial sense, since starting from a rate of zero star formation to a finite star formation rate mathematically requires an acceleration. However, it also occurs naturally in our evolutionary model of molecular cloud formation. The Gf1 and Gf2 simulations shown in Figures 1 and 2 show that a few dense concentrations show up by 10 Myr or so (see also the core mass history; Fig. 5 in H08b). One can easily infer that, if we had sufficient resolution, we would observe a few stars being formed from the very densest of the dense concentrations first; later on, as global and local collapse proceeds, more and more stars would form.

Our simulations emphasize that the global age spread in a star-forming region is an upper bound to the timescales of local collapse, as compressions will never be perfectly coordinated in time across any given cloud.

4.4. The Onset of Star Formation

In our model, turbulence generated through the cloud formation process provides a mechanism to produce thermal and dynamical fragmentation. While this fragmentation is highly efficient in generating cold, high-density cloudlets, the “preformation” of
such cloudlets is limited by the minimum Jeans mass achievable. With $c_s$ denoting the (isothermal) sound speed, we have

$$M_{\text{J}} \approx \left(\frac{\pi c_s^2}{G}\right)^{3/2} \rho^{-1/2} \sim 570 T_\text{mol}^2 \bar{P}_\text{ram}^{-1/2} M_\odot,$$

where $\bar{P}_\text{ram} = \bar{\rho}_i v_i^2$, again in units of our simulations. To form, e.g., solar-mass objects, higher pressures are needed. Since invoking “supersonic turbulence” as a fragmentation mechanism in its own right without specifying its physical source is somewhat unsatisfactory, the only remaining free energy source leading to a self-consistent picture of the formation of prestellar cores is gravity (e.g., Bertoldi & McKee 1992; Field et al. 2008).

We have already seen that gravity helps along the “CO formation” in our clouds (Figs. 1 and 2), and also that unless the simulations include gravity, they are not going to form the high-density cores with free-fall times $\tau_f < 1$ Myr (Fig. 5). Figure 7 demonstrates that it is gravity which eventually leads to the high pressures required for fragmentation into small masses. It shows the mass-weighted pressure histograms of models Hf1 and Gf1 in the same time sequence as in, e.g., Figure 1. At $t = 5.3$ Myr, the distributions are indistinguishable. With increasing time, gravity drives more and more mass to higher pressures, until the pressure distribution follows the Jeans mass (eq. [9]) at the lowest temperature threshold (blue dashed line). In contrast to model Gf1, the pressure distribution of model Hf1 stays more or less constant with time.

4.5. Turbulent Support

It has been claimed that the loss of turbulent support (e.g., Huff & Stahler 2007) would lead to an (accelerated) star formation in molecular clouds (Palla & Stahler 2000, 2002). A closer look at the energy budget (Fig. 8) in our model clouds, however, reveals that in the context of flow-driven cloud formation, it is actually the buildup of mass and thus the deepening of the gravitational potential well which leads to collapse, but not the loss of turbulence (see also Fig. 8 of Vázquez-Semadeni et al. 2007). The energy densities were calculated using only gas at $T < 50$ K, approximately corresponding to the molecular gas. The internal energy (black lines) stays constant, while the gravitational energy (green lines) increases with time, offsetting the slight decrease in kinetic energy (red lines).
Second, nonuniform inflows will increase the level of turbulence in the resulting cloud, as demonstrated by Dobbs & Bonnell (2007a). They found the slope of the line width–size relation to flatten with increasing filling factors of the clumpy inflows. Third, the dynamical range for gravitational collapse in our models is somewhat limited, possibly suppressing turbulent motions once the cloud has collapsed.

We take the discussion of the perceived loss of turbulent support as an opportunity to demonstrate how the star formation in our models (strictly speaking, we are only forming cores) would be represented by the normalized “star formation rate” of Krumholz & McKee (2005) and Krumholz & Tan (2007):

\[
\text{SFR}_\text{F} \equiv \frac{\dot{M}}{M(>n)} \tau_\text{F}. \tag{10}
\]

Here, \(M(>n)\) is the mass of the cloud above a density threshold \(n\), \(\dot{M}\) is the star formation rate, and \(\tau_\text{F}\) is the free-fall time at a given density. The choice of this density obviously will affect the results. Figure 10 shows the SFR\(_F\) as defined above, for various times against the threshold density \(n\) (model Gf1). As a proxy for the star formation rate \(\dot{M}\) we use the time derivative of the mass accretion history (see, e.g., symbols in Fig. 4). This includes the formation of new cores as well as the mass accretion onto already formed cores. It is also consistent with the estimates of \(\dot{M}\) from the simulations discussed by Krumholz & Tan (2007).

At early times \((t = 11.4, 12.2 \text{ Myr})\), the models are consistent with the analytical predictions (see Fig. 5 of Krumholz & Tan 2007): the SFR\(_F\) ranges around a few percent. Obviously, it is a matter of interpretation whether this low percentage is to be seen as “slow” star formation: especially at the lower density thresholds, the free-fall time \(\tau_\text{F}\) is not representative of the local conditions under which the “stars” form. At later times, several effects are discernible. For low-density thresholds (i.e., considering the “whole” cloud; see also Fig. 5), still SFR\(_F\) \(\lesssim 10\%\). For higher density thresholds (i.e., selecting for the regions that are locally collapsing in the simulation), the SFR\(_F\) increases but stays short of \(\approx 50\%\). This is not surprising, since (1) these regions are not resolved, i.e., they would not convert all their mass into stars so that the “real” SFR\(_F\) would be substantially lower; and (2) our models do not include feedback. Moreover, the models discussed here are an extreme realization of a range of scenarios whose other extreme would be a perfect shear flow (D. M. Williams et al. 2008, in preparation). With a larger component of shear or angular momentum, the SFR\(_F\) could be reduced even further.

4.6. Other Limitations

In addition to limited resolution, our models do not include stellar energy input, which is the most plausible mechanism to reverse the collapse of our self-gravitating molecular clouds. It is difficult to see how stellar energy input can exactly balance the nonlinear variation of gravity with position within the cloud; there is more parameter space for either expansion or contraction. We note that even at the end of our simulations, most of the mass of the cloud, including that of the molecular (CO) regions, has long free-fall times and low densities. The low filling factors indicated by the SFR\(_F\) at \(n \approx 100 \text{ cm}^{-3}\) and by Figure 5 suggest that stellar feedback can in principle blow away most of the cloud mass and thus keep overall star formation efficiencies low (see also Elmegreen 2000). While this remains an important issue of our scenario which needs further investigation, it should also be pointed out that to our knowledge there are no simulations of long-lived clouds that are not computed with periodic boundary conditions, the adoption of which begs the question.

Magnetic fields could in principle suppress or affect the fragmentation (e.g., Field 1965) for the thermal instability; Heitsch...
et al. [2007] for the dynamical instabilities in colliding flows), although this capability seems to depend strongly on the number of dimensions considered (e.g., Inoue & Inutsuka 2008). Also, the sheer accumulation of mass along field lines might render the fields less important than commonly thought, as demonstrated in numerical models by Hennebelle et al. (2008).

5. SUMMARY

Making a simple but reasonable approximation for the formation of CO from atomic gas, we have shown that the formation of molecular clouds from large-scale flows can be tied closely to the formation of self-gravitating structures. Our numerical simulations support many parts of the rapid cloud and star formation scenario, in particular the rapid appearance of CO in self-gravitating clouds, quickly followed by the formation of dense cores with free-fall timescales of order 1 Myr, and that global gravitational collapse plays an important role in cloud evolution. The simulations reproduce expected low star formation rates at early times. For the long-term evolution of the star formation history and the molecular cloud itself, the issue of stellar energy input (feedback) needs to be addressed to develop a more comprehensive picture of star formation in the solar neighborhood.

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Fig. 10.—Star formation rate normalized by the free-fall time $SFR_f$ (eq. [10]). The plot has been generated following the recipe given by Krumholz & Tan (2007), i.e., the free-fall time is computed for the mean (left) and median (right) density above the density threshold given on the $x$-axis. Symbol sizes indicate simulation times.
