EFFECTS OF MAGNETIC FIELD STRENGTH AND ORIENTATION ON MOLECULAR CLOUD FORMATION

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ABSTRACT

We present a set of numerical simulations addressing the effects of magnetic field strength and orientation on the flow-driven formation of molecular clouds. Fields perpendicular to the flows sweeping up the cloud can efficiently prevent the formation of massive clouds but permit the buildup of cold, diffuse filaments. Fields aligned with the flows lead to substantial clouds, whose degree of fragmentation and turbulence strongly depends on the background field strength. Adding a random field component leads to a “selection effect” for molecular cloud formation: high column densities are only reached at locations where the field component perpendicular to the flows is vanishing. Searching for signatures of colliding flows should focus on the diffuse, warm gas, since the cold gas phase making up the cloud will have lost the information about the original flow direction because the magnetic fields redistribute the kinetic energy of the inflows.

Key words: instabilities – ISM: clouds – methods: numerical – MHD – stars: formation – turbulence

Online-only material: color figures

1. MOTIVATION

Evidence is accumulating that star formation follows rapidly upon molecular cloud formation (e.g., Hartmann et al. 2001 and Ballesteros-Paredes & Hartmann 2007 for the solar neighborhood; Engargiola et al. 2003 for M33; Elmegreen 2007 in the context of M51). This rapid onset suggests that the clouds need to acquire high, nonlinear density enhancements during their formation, since massive, finite clouds are highly susceptible to global gravitational collapse which could overwhelm small-scale fragmentation necessary for (local) star formation (Burkert & Hartmann 2004). Thus to understand the initial conditions for star formation, we need to understand the formation of the parental clouds.

Ballesteros-Paredes et al. (1999) and Hartmann et al. (2001) proposed that the buildup of clouds in large-scale, converging flows of diffuse atomic gas could explain the crossing time problem, i.e., the observation that the stellar age spreads in a large number of local star-forming regions are substantially smaller than the lateral crossing time (Hartmann et al. 2001; Ballesteros-Paredes & Hartmann 2007). In this picture, there need not be a causal connection between star formation events in the plane perpendicular to the large-scale flows (see also Elmegreen 2000). Rapid star formation is a necessary requirement for this scenario to work.

Numerical models of flow-driven cloud formation (we give only an early and the most recent numerical work of each group, namely Hennebelle & Pérault 1999 and Hennebelle et al. 2008; Koyama & Inutsuka 2000 and Inoue & Inutsuka 2008; Heitsch et al. 2005 and Heitsch et al. 2008b; Vázquez-Semadeni et al. 2006 and Vázquez-Semadeni et al. 2007) have identified the thermal and dynamical instabilities that are responsible for the rapid fragmentation of the nascent cloud (see Heitsch et al. 2008a for an assessment of the roles of the physical processes). Despite these promising successes, many questions about the physics at play remain unanswered, among one of the most pressing is the role of magnetic fields during the cloud formation process.

The role of magnetic fields in the flow-driven cloud formation scenario has been largely envisaged as one of “guiding the flows” to assemble the clouds, whether in form of the Parker instability along galactic spiral arms (Parker 1966, 1967; Mouschovias et al. 1974, 2009), in a generally turbulent interstellar medium (ISM) (Passot et al. 1995; Hartmann et al. 2001), or during the sweep-up of gas in spiral shocks (Kim & Ostriker 2006; Dobbs & Price 2008). Based on the models of Passot et al. (1995), Hartmann et al. (2001) suggested that the field orientation with respect to the flows selects the locations of cloud formation, namely that clouds will only form if the fields are aligned with the flows. A perpendicular field will reduce the compression of the post-shock gas and thus will limit the strong cooling and the thermal instability (TI, Field 1965) necessary for the rapid flow fragmentation and the buildup of high-density contrasts (Burkert & Hartmann 2004; Heitsch et al. 2008b, 2008a).

Given sufficiently high strengths, fields aligned with the inflows can suppress the dynamical instabilities responsible for the generation of turbulence, namely the nonlinear thin shell instability (NTSI, Vishniac 1994; for a magnetic version see Heitsch et al. 2007) and the Kelvin–Helmholtz instability (KHI, e.g., Chandrasekhar 1961, more recently Kunz 2008, and for numerical studies Palotti et al. 2008). Yet magnetic fields are intrinsically three dimensional, and already two-dimensional models by Inoue & Inutsuka (2008) show that even for fields perpendicular to the inflow, cold (albeit diffuse) clouds can form.

Thus, three-dimensional models of flow-driven cloud formation including magnetic fields are needed. Hennebelle et al. (2008) present a first approach to the problem, modeling the formation of a cloud in converging, perturbed flows, including fields and self-gravity. Here, we focus on the effects of magnetic field strength and orientation on the early stages of flow-driven cloud formation. We work in the ideal magnetohydrodynamic (MHD) limit (i.e., we do not explicitly consider ambipolar drift or resistivity), and we do not include gravity in the models.

All our models start out with field strengths below equipartition with the kinetic energy of the inflows. At a factor of 4.3 below equipartition—corresponding to an absolute field strength of 5 μG at flow densities and velocities of 1 cm−3 and...
16 km s$^{-1}$—the fields already suppress the dynamical instabilities (and thus the generation of turbulence) leading to slab-like molecular clouds, while weaker fields—at 2.5 $\mu$G, corresponding to a factor of 17 below equipartition—lead to clouds closely resembling the hydrodynamical case, albeit with more coherent filaments. Fields at 0.5 $\mu$G perpendicular to the inflows suppress the buildup of massive clouds in the collision plane, while they lead to the formation of diffuse, cold filaments perpendicular to the mean field, reminiscent of the cold H I clouds discussed by Heiles & Troland (2003; see also Abel et al. 2004, 2006). A tangled field allows the assembly of substantial column densities in regions where the lateral field component is small or vanishing. Our results are consistent with the notion that magnetic fields select the location of cloud formation (Hartmann et al. 2001).

2. TECHNICAL DETAILS AND PARAMETERS

2.1. Athena

Calculations were performed with Athena (Gardiner & Stone 2005, 2008), an unsplit, second-order accurate Godunov scheme, using the corner transport upwind method (Gardiner & Stone 2008) and a linearized Roe solver (Roe 1981). The divergence of the magnetic field is kept zero by using constrained transport (Evans & Hawley 1988). Dissipative terms (viscosity, heat conduction and resistivity) are not explicitly included. For a detailed description and test results, the reader is referred to Gardiner & Stone (2005, 2008) and Stone et al. (2008).

We implemented heating and cooling as an additional energy source term. A tabulated cooling function provides the energy change rate as a function of density and temperature at each grid cell. We decided to keep the iterative approach we had used in our earlier studies of cloud formation (Heitsch et al. 2005, 2006, 2008b), with a slight modification. Instead of advancing the fluid evolution at the usual time step given by the Courant–Friedrichs–Levy (CFL) condition and subcycling on the energy–momentum equation in case the cooling timescale is shorter than the CFL time step, we lower the CFL time step according to

$$\Delta t = \Delta t_{\text{CFL}} \min(1, (\tau_c/\Delta t_{\text{CFL}})^p),$$

with $0 \leq p \leq 1$. For increasing $p$, small cooling time steps will control the overall CFL time step. The earlier version (see references above) would be equivalent to $p \equiv 0$. Yet this choice can lead to inconsistencies in the hydrodynamical evolution once the cooling time steps get substantially shorter than the fluid time steps, leading to a numerical overemphasize of the acoustic mode of the TI, since regions can cool substantially without accounting for the resulting pressure drop in the dynamics. While these inconsistencies may not affect the overall results, they turn out to affect the stability of the solution. For the models presented here, $0.5 < p < 0.7$ yields a stable and accurate solution. While the iterative approach is more time consuming than a direct integration as suggested by e.g., Vázquez-Semadeni et al. (2007), it allows us to take into account the increasing thermal timescale of a fluid parcel cooling down toward the thermal equilibrium line (see, e.g., Figure 3 of Heitsch et al. 2008a). This effectively keeps a fraction of 40%—50% of the gas mass in the thermally unstable warm neutral medium (WNM), consistent with observed fractions (Heiles & Troland 2003; also Section 3.3).

2.2. Setup and Parameters

The initial conditions and flow parameter are similar to those used in our earlier work (Heitsch et al. 2008b). Two identical uniform flows collide head-on at an interface whose position is perturbed using an amplitude that is chosen randomly, but with the constraint that only the long wavelengths (down to a quarter of the box size) are nonzero. The maximum perturbation amplitude measures 10% of the box size. The flows are otherwise in thermal equilibrium and do not have a substructure. Thus, we can test the most unfavorable conditions for the substructure and turbulence generation in the resulting clouds.

The simulation domain has a resolution of $256^3$, and the linear box size measures 44 pc in all cases, resulting in a nominal resolution of 0.18 pc. The boundaries in $y$ (and $z$) are periodic, while those in $x$ are set to a constant inflow speed of $v_0 = 16$ km s$^{-1}$, a density of $n_0 = 1$ cm$^{-3}$, a temperature of $T_0 = 8 \times 10^3$ K, and a magnetic field (if applicable). The adiabatic exponent $\gamma = 5/3$. The flow speed $v_0$ is consistent with shock speeds along streamlines passing through Galactic spiral shocks at the solar circle (Shu et al. 1972). Our thermal pressure is a factor 2–3 higher than the pressures estimated for the CNM/WNM (Jenkins & Tripp 2001; Heiles & Troland 2003), increasing the ratio of thermal over magnetic pressure $\beta_p$ above observed values (Heiles & Troland 2005, hereafter HT05). Yet the measure relevant for the dynamical importance of magnetic fields is the ratio of the ram pressure over the magnetic pressure, $\beta_{\text{ram}}$, since the instabilities responsible for turbulence generation and fragmentation depend on the ratio of the flow velocities over the Alfvén speed (Chandrasekhar 1961; Heitsch et al. 2007). In the diffuse, local ISM, kinetic and magnetic energy are in approximate equipartition ($\beta_{\text{ram}} \approx 1$; HT05), while in regions of ordered, large-scale flows—such as Galactic spiral shocks or expanding supernova shells—with $v_0 \gtrsim 10$ km s$^{-1}$, $\beta_{\text{ram}} > 1$ should be expected.

There are four classes of models: hydrodynamical (series H), field aligned with flow (series X), field perpendicular to the flow (series Y), and (series XR) a uniform field component aligned with the flow plus a random field component of the same amplitude, consistent with (although a little smaller than) observed magnetic field strength estimates (e.g., Heiles 1996; Beck 2004b; Han 2006). In the latter series, we do not perturb the collision interface but rely on the tangled field component to trigger the dynamical instabilities. Table 1 summarizes the model parameters. Self-gravity is not included in the models.

To initialize the random field component, we set the amplitudes and phases of e.g., the $x$-component of the (edge-centered) vector potential to

$$A_x(x, y, z) = \sum_{i,j,k=1}^{\text{max}} |k|^{-n} \sin (k_i x + k_j y + k_k z + \phi_{i,j,k}^x),$$

where $k = (k_x, k_y, k_z)$ is the wave number of the respective Fourier mode, $\phi_{i,j,k}^x$ is a random phase in the interval $[0, 2\pi]$, and $n$ is the power law for the power spectrum of the random field component. The power spectrum of the random field component is $|k|^{-3}$, corresponding to an energy spectrum of $|k|^{-5}$, where $k$ is the wave number. The power law for the power spectrum of the random field component is $|k|^{-3}$, corresponding to an energy spectrum of $|k|^{-5}$, where $k$ is the wave number.
where \( |k| \equiv k_x^2 + k_y^2 + k_z^2 \) and e.g., \( k_z \equiv 2\pi i/L_z \) with the box length \( L_z \). We set \( p \equiv 4 \), mimicking a (steep) turbulent energy spectrum as observed in detailed numerical simulations of MHD turbulence (e.g., Cho & Lazarian 2003). The wavenumbers \( k_x, k_y, k_z \) are chosen such that \( 1 \leq |k| \leq 4 \), i.e., all combinations of \((i, j, k)\) in the sum over \( k\)-space are used that satisfy the constraint on \(|k|\). The phases \( \phi_{i,j,k}^x, \phi_{i,j,k}^y, \phi_{i,j,k}^z \) in \( k\)-space are chosen from a uniform random distribution. Each vector potential component \( A_{i,x,y,z} \) requires a separate phase array \( \phi_{i,x,y,z} \).

This formulation in real space instead of in Fourier space (see e.g., Mac Low et al. 1998; Stone et al. 1998; Lemaster & Stone 2008 for velocity fields) allows us to easily regenerate the vector potential (and the field) at the inflow boundaries by

\[
A_i(\pm L_x/2, y, z, t) = A_i(\pm (L_x/2 + v_0 t), y, z), \quad (3)
\]

where the negative value refers to the lower \( x\)-boundary and the positive to the upper one. The face-centered fields are then computed from the vector potential by \( \mathbf{B} = \nabla \times \mathbf{A} \).

The choice of the wavenumber range \( 1 \leq |k| \leq 4 \) does not constitute a restriction in terms of generality of our simulations, since the energy distribution over spatial scales is determined by the (steep) power law index \( p \). This is fortunate in a sense, since the generation of the boundary conditions (Equation (3)) would consume substantially more time if we had to sum over all available \(|k|\) in Equation (2).

### 2.3. Physical Interpretation of the Initial Conditions

Obviously, our initial conditions are somewhat idealized, e.g., generally, the flows would be expected to have substructure, the flows might not be expected to collide always head-on, and the magnetic fields will have parallel and perpendicular components with respect to the inflows. Yet the initial conditions can be seen as idealized versions of different physical environments.

The case of uniform fields aligned with the inflows (models X25, X50) could be identified with the sweep-up of material by an expanding supernova shell along an ordered background field, or with the collision of two expanding shells in such a field. The initial field strength of 5 \( \mu G \) (model X50) is close to the local median (total) field strength in the CNM (e.g., HT05; Troland 2005). Using Nakano & Nakamura’s (1978) expression for the critical surface density \( N_c \equiv B/\sqrt{4\pi\sigma T G} \) above which gravitational collapse is possible under flux-freezing conditions, the swept-up clouds would reach approximately 0.5\( N_c \) after 12 Myr, while model X25 (\( B_0 = 2.5 \mu G \)) would be marginally critical at the same time. We defer the discussion of the mass-to-flux ratio in the clouds to a subsequent paper including gravity.

An ordered field aligned with the flows plus a large-scale random component of similar amplitude (model XR25) introduces a large-scale shear and might be considered a general situation for sweep-up of gas in spiral shocks, while the perpendicular field case (Y05) would address the (probably common) situation of an oblique field whose lateral component is amplified by flow compressions.

We emphasize that while we attempt to address the extreme situations of field orientations, the finite size of our simulation domains cannot fully capture the effects of the magnetic field’s boundary conditions. These will be set on larger scales than our local simulations can cover. In that sense, our results should be viewed as providing insight into magnetized cloud formation under idealized conditions rather than under physically realistic ones.

### 2.4. A Comment on Resolution

We decided to keep the resolution of our models constant, foregoing a resolution study in favor of a parameter study. Resolution effects have been discussed by Hennebelle & Audit (2007). In addition, we have performed a systematic resolution study for two-dimensional cloud formation models (unpublished—the models are similar to the ones discussed by Heitsch et al. 2005, 2006), covering a factor of 32 in spatial resolution (from \( 256^2 \) to \( 8192^2 \) cells). As has been pointed out, the critical length scale to resolve is the cooling length of the thermal instability. If not resolved, the thermal instability will be partially suppressed. At parameters of the WNM, the cooling length is on the order of a parsec, while for the cold neutral medium (CNM), it drops to a fraction of a parsec. Thus, while more substructure should form with increasing resolution, we expect our models to follow the general evolution of the thermal and dynamical instabilities sufficiently accurately for our purposes.

### 3. RESULTS

#### 3.1. Morphologies

Figure 1 summarizes the morphological effects of magnetic fields during the build up of a cloud. From top to bottom, it shows logarithmic column density maps of the hydrodynamical model H, and the four MHD models X25 through XR25. The three columns stand for projections along each coordinate axis, namely along the inflow (\( x \)-axis, left), and perpendicular to the inflow (along the \( y \) and \( z \)-axes, center and right). The maps of the MHD models show polarization vectors which have been determined by integrating the density-weighted Stokes \( Q \) and \( U \) parameters along the respective line of sight (see Zweibel 1996; Heitsch et al. 2001).

#### 3.1.1. Field Parallel to Inflow

Model H shows the strong fragmentation due to thermal and dynamical instabilities similar to the models discussed by Heitsch et al. (2008b). Specifically, the large-scale initial perturbation triggers the NTSI, due to whose rapid growth some of the dense material has already reached the inflow boundaries. Viewed along the inflow (top left panel in Figure 1), the cold dense fragments appear clumpy rather than filamentary.

Introducing a magnetic field \( \textit{aligned} \) with the flow (model X25, second row) suppresses fragmentation compared to model H. The face-on view (left) shows several large-scale coherent filaments with denser cores. The edge-on views (center and right) demonstrate that the magnetic field is not dynamically dominant. The polarization vectors are aligned with local structures.

Increasing the magnetic field (model X50, third row from top) seems to suppress much of the fragmentation. Specifically, the NTSI is only very weakly (if at all) present, since the magnetic field is strong enough to suppress the lateral momentum transport necessary for triggering the NTSI (Heitsch et al. 2007). Nonetheless, the flows still fragment, albeit into a tight network of filaments (X50, left) instead of a few large, more clumpy and fuzzy structures (models H, X25). The suppression of the NTSI leads to the formation of a more or less coherent filament in the lateral projection (center and right column for model X50). Local shear modes lead to strong distortions of the field from its initial alignment with the inflow, as indicated by the polarization vectors which mostly trace out the mean background field.
3.1.2. Field Perpendicular to Inflow

The introduction of a field perpendicular to the inflow changes the morphology completely (fourth row of Figure 1, model Y05), despite the by a factor of 10 weaker field (see Table 1). The perpendicular field breaks the symmetry in the plane of the flow collision, leading to filaments perpendicular to the mean field direction (note that the mean field in the left...
panel of the fourth row of Figure 1 is oriented horizontally). These filaments form due to motions along the field lines, but perpendicular to the incoming flows (see also Heitsch et al. 2007 and Inoue & Inutsuka 2008 for two-dimensional models). The magnetic field suppresses one degree of freedom in the gas motions, also leading to lower column density contrasts than in models H and X50. The two lateral views of model Y05 exhibit another effect of the perpendicular field. Seen along the mean field direction, a large scale NTSI-driven mode is discernible, while the projection perpendicular to the inflow and to the mean field (Y05 right) just shows a slab (albeit with substructure). In the former, the field lines are just shuffled around and contribute to the dynamics only via the pressure term in the Lorentz force, thus lowering the column densities and broadening the slab (compare to center panel of model X50). In the latter case, the tension term of the Lorentz force prevents the growth of the NTSI. This is evidence for the presence of interchange modes in the NTSI, similar to e.g., the Rayleigh–Taylor instability (Stone & Gardiner 2007). Still, material is free to move along the field lines (and thus perpendicular to the inflows), leading to the formation of the filaments parallel to the inflows.

The magnetic field perpendicular to the inflow resists compression, leading to a suppression of the thermal instability, which is also mirrored in the total mass budget of all models (Figure 2). Model X50 has the highest fraction of cold gas, due to the strong guide field leading to a strong compression of the gas, while model Y05 shows the smallest cold mass fraction, because the lateral field resists compression by the flows, and thus reduces the cooling rates.

3.1.3. Tangled field

The bottom row of Figure 1 shows the maps for model XR25, which starts out with a uniform field aligned with the flow at 2.5 \( \mu G \) and a random field component of equal magnitude. Although the (varying) lateral field components contain 10 times as much energy as the perpendicular field in model Y05, the fields do not suppress the formation of clouds with column densities in excess of \( 10^{22} \) cm\(^{-2} \); a tangled field is substantially less efficient in preventing compression. Since there are regions where the field will be aligned with the flow, it leads to a selection effect in the sense that the clouds form at positions where the lateral random components of the fields are weakest over time and/or where bends in the fields determine the position of cloud formation (see Hartmann et al. 2001). The resulting clouds are more isolated, with larger voids between them (bottom left panel of Figure 1). The side view (bottom center and right) exhibits a diffuse halo of thermally unstable gas, material which is caught in the tangled field between the bounding shocks and the dense cold gas.

3.2. Dynamics

The cold mass fractions of models H and X25 (Figure 2) are slightly lower than that of X50, indicating that the developing turbulence due to the flow fragmentation is also broadening the slab. While this notion is already suggested by Figure 1, it is confirmed by comparing the rms velocity dispersion in the cold \( (T < 300 \, \text{K}) \) gas (Figure 3), and it can also be gleaned from a more detailed look at the laterally averaged pressure profiles (Figure 4).

Shown is a time sequence of the pressure profiles along the \( x \)-axis (i.e., along the inflows) for all models. In the absence of gravity, the slabs are all overpressured by the ram pressure of the colliding flows (solid lines). At early times, all five models show a drop in kinetic pressure and an increase in thermal pressure in the collision region. The flows have not fully fragmented yet, and the cooling is not in full strength yet because of the still low densities. With evolving time, the thermal pressure peak for model H drops due to increasing cooling.

This is markedly different for model X50, where the thermal pressure continues to be enhanced by a factor of more than 2 above that of the inflow. Also, the kinetic pressure drops, reaching an approximate equipartition with the thermal pressure. This is due to the strong magnetic guide field, which “splits” the cloud into a network of dense filaments with low-density, high-temperature voids in between (see the top panel of the second column of Figure 1, model X50). Figure 5 offers a different view of the same phenomenon, showing the pressure-density distributions for all four models, at \( t = 9.5 \, \text{Myr} \).

The high-temperature voids of model X50 show up at \( \log n \approx 0.5 \) and \( \log P \approx 4.3 \), while the high-density filaments sit all on the stable low-temperature branch of the thermal equilibrium curve at \( T \approx 40 \, \text{K} \). Note that a substantial amount of the gas mass is actually thermally over-pressured, in contrast to model H.

Reducing the field aligned with the flow (model X25) leads to pressure profiles (Figure 4) and thermal states (Figure 5) similar to the hydrodynamical model H. In other words, while the field
in model X25 is non-negligible in the sense that its presence still makes a morphological difference (see Figure 1), it does not noticeably affect the overall dynamics of the cloud.

The field is obviously dynamically important in model Y05. Because of the strong flow compression perpendicular to the field lines, the magnetic pressure takes over the role of the thermal pressure, which leads to a substantial amount of thermally underpressured gas in model Y05 (Figures 4 and 5). There is only a small amount of material at high ($\log n > 2$) densities.

Introducing the tangled field component on top of a field aligned with the inflows leads to an over-pressurization of the slab by a factor of more than 2 (Figure 4 right, model XR25). This is mainly due to a combined increase in magnetic and kinetic pressure, i.e., the tangled field leads to more turbulence than all other field geometries. The increase in kinetic pressure cannot be solely due to enhanced densities—model X50 should show a similar increase then. Although the tangled field in the diffuse gas phase is not force-free, it does not contribute perceptibly to turbulent motions in the inflows, as can be seen by comparing the kinetic pressure levels in the inflows between models XR25 and e.g., X50. Also, the kinetic pressure of model XR25 does not increase when moving closer towards the midplane, until one enters the postshock region. The thermal pressure peaks in the diffuse envelopes due to warm gas being unable to cool down (see bottom right panel of Figure 5), but it

**Figure 4.** Pressure profiles along the inflow direction ($x$), averaged over the perpendicular directions ($y, z$), for 3 times as indicated, and for all models. Shown are total (solid line), kinetic (dashed), internal (dash-dot) and—if applicable—magnetic (dash-3-dot) pressures. Note that we show the pressures, not the logarithm of the pressures.

**Figure 5.** Gray scale-coded mass fraction of thermal pressure against volume density for all models as indicated in the plots, at $t = 9.5$ Myr. The solid line indicates the thermal equilibrium curve, while the vertical and horizontal dashed lines denote the initial conditions in density and pressure. Diagonal dashed lines stand for isotherms at $T = 10^4, 300$ and 10 K as indicated.
Figure 6. Pressures against time for all models, sorted according to temperature regimes (rows; total, $T > 3000$ K, $300 < T < 3000$ K and $T < 300$ K) and components (columns; total, $x$, $y$, and $z$). Black lines indicate thermal pressure, red lines kinetic and blue lines magnetic pressure. Note that these are again linear pressures in units of $10^4$ K cm$^{-3}$.

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

drops back to the ambient thermal pressure at the cloud midplane ($x = 0$). Obviously, the averaged thermal pressure alone is not a very accurate indicator of the cloud’s physical state.

Figure 6 summarizes the pressure evolution over time for all models. The pressures are sorted according to temperature regimes (rows; total, stable WNM, unstable WNM, and CNM) and vector components (columns; total, $x$ parallel to inflow, $y$ perpendicular to inflow, and $z$ again perpendicular to inflow). The total pressures (top row) stay constant with time except for the magnetic components of models XR25 and Y05 due to the compression of the transverse field component (see the $y$ column), and the $y$-component of the kinetic energy of model XR25. Not surprisingly, the stable warm neutral phase does not show any strong pressure variations with time. In the thermally unstable regime, $300 < T < 3000$ K, the models with transverse field components (XR25, Y05) show an increase in the $y$ and $z$ component of the magnetic pressure. A large fraction of the magnetic energy in model XR25 is thus stored in the diffuse cloud halo (see Figure 1). The magnetic fields also lead to a “redistribution” of kinetic energy between the vector components: the bulk of the kinetic energy of the cold gas in model H is found in the $x$-component, parallel to the inflow, indicating that the dynamics are dominated by the NTSMs. The magnetic field models have at least as much kinetic energy in the transverse ($y$ and $z$) components. For model XR25, the transverse components even dominate. The substantial overpressure at the midplane of model XR25 (see Figure 4) arises mainly from the transverse components of the magnetic and kinetic energy in the cold gas. While for $T < 300$ K, the magnetic energies are larger than the kinetic ones, the kinetic energy content dominates the total energy budget (top left panel of Figure 6).

Figure 7 offers a simpler view of the field amplification depending on mean field direction. It shows the ordered (mean) field component and the random (turbulent) component against the time. Only the random components are growing with time, indicating that the fields are mainly amplified by field-line stretching. Only models Y05 and XR25 have field components initially perpendicular to the inflows; these are growing linearly with time due to the compression by the flows. The random (or turbulent) field components of models X25 and X50 evolve in a similar way, indicating that a similar amount of energy is stored in the random component. For models X25 and Y05, the ordered and random components reach similar levels (see Section 4.3).
3.3. Turbulence and Thermal States

The ratio of gas mass in the thermally unstable regime to the mass in the WNM can be compared to observational constraints. Heiles & Troland (2003) find a fraction of 48%. Figure 8 shows the mass fractions for all models against the velocity dispersion in the CNM, averaged over a time interval $7.5 < t < 9.5$ Myr. Higher fractions of thermally unstable gas are found at higher velocity dispersions, a correlation already pointed out earlier (e.g., Gazol et al. 2001; Audit & Hennebelle 2005; Heitsch et al. 2006; Hennebelle & Audit 2007). However, the magnetic field introduces a second dependency: of the three models with the highest velocity dispersion (H, Y05 and XR25), model Y05 has the highest fraction of thermally unstable gas. As discussed above, in this model the lateral field components reduce the density contrasts, keeping a substantial fraction of the gas in the thermally unstable regime. The large velocity dispersion of model Y05 arises from the large-scale NTSI interchange mode (see Figure 1).

It is maybe not surprising that the structures which bear closest resemblance to the CNM clouds studied by Heiles & Troland (2003, 2005) belong to the model with a thermally unstable mass fraction closest to the observed one (Y05).

4. DISCUSSION

4.1. The Role of Magnetic Fields for Cloud Formation

The field strength, and the orientation of the mean magnetic field with respect to the flows sweeping up the gas play a crucial role for the flow-driven formation of molecular clouds (Figure 1). If the fields are dynamically dominant, the only chance to build up substantial clouds is by channeling the flows along the fields. This is the situation shown in model X50, and it is also borne out by simulations of molecular cloud formation in galactic spiral arms (Kim & Ostriker 2006), where the clouds tend to be oriented perpendicularly to the large-scale field (also possibly visible in the models by Dobbs & Price 2008), until sufficient material has been accumulated that they decouple dynamically from the large-scale field. Similarly, for the sweep-up of material by e.g., HII-regions or supernova shells, one would expect the densest clouds to appear at the locations where the field is perpendicular to the shell (see Figure 2 of Hanayama & Tomisaka 2006, although the effect might be less clear in a highly turbulent environment, see Figure 10 of Balsara et al. 2004).

Hartmann et al. (2001) point out—based on simulations by Passot et al. (1995)—that dynamically weak (but not necessarily ordered) fields would lead to a general selection effect for the formation of molecular clouds. Since $\beta_{\text{ram}} > 1$, the flows stretch out the field lines, leading to a natural alignment. In this picture, clouds form in the bends of large-scale fields (see Figures 4 & 5 of Hartmann et al. 2001). Such a scenario is to some extent addressed by model XR25, where varying field orientations entail a local selection effect, picking out the formation sites of molecular clouds over e.g., a broad shock front. Note that while the field is dynamically weak ($\beta_{\text{ram}} = 8.5, \beta_{\text{th}} = 4.3$) in the initial conditions (and in the inflows) of model XR25, $\beta_{\text{th}} < 1$ within the cloud (Figure 4).

This selection effect comes about because already a small oblique component can be amplified sufficiently to withstand the compression, preventing the high densities needed for cloud formation (Hartmann et al. 2001). Such a situation is addressed in the extreme by model Y05. A field perpendicular to the sweeping-up flow can suppress the formation of massive clouds, although the three-dimensional situation is much less clear-cut than its one-dimensional counterpart (see, e.g., McKee & Hollenbach 1980; Bergin et al. 2004). In one dimension, a density increase by a factor of 100 from e.g., $n = 1 \text{ cm}^{-3}$ to $100 \text{ cm}^{-3}$ would entail the same factor for the magnetic field strength since $B \propto n$. Figure 9 shows this is not the case in three dimensions. The weak perpendicular field (model Y05) has been amplified by a peak factor of $\approx 30$, while the density has increased by up to a factor of 300. Generally, our models show a weak correlation of field strength with density over the whole thermal range, from the WNM to the CNM, consistent with observations of the field-density relation in the WNM and CNM (Troland & Heiles 1986; HT05), and with numerical results (e.g., de Avillez & Breitschwerdt 2005; Hennebelle et al. 2008). For models X50 and X25 a weak correlation between field and density is not overly surprising. For model Y05, the decorrelation3 is a consequence of the fact that material is still free to move along the field lines perpendicular to the original

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3 The seemingly strongly correlated $B(n)$ for $n < 1 \text{ cm}^{-3}$ in model Y05 does not affect the argument. These are a few regions (low mass fraction) at the edges of the expanding slab, subjected to numerical reconnection.
Figure 9. Magnetic field strength against volume density for models as indicated in the plots. The colors denote temperatures, and the intensity the mass fraction. Generally, there is no clear correlation between field strength and density. The steeper of the two dashed lines denotes $B \propto n$, the flatter one $B \propto n^{1/2}$. Dotted lines denote the initial conditions.

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

inflow (Heitsch et al. 2007), thus leading to the buildup of higher-density filaments perpendicular to the field (but aligned with the inflow), see Figure 1. Also, other effects, such as the acceleration of magnetic field transport by turbulence (Zweibel 2002; Fatuzzo & Adams 2002; Heitsch et al. 2004 for ion-neutral drift, Lazarian & Vishniac 1999 for reconnection), or a decorrelation due to MHD waves (Passot & Vázquez-Semadeni 2003) could explain the observed weak correlation.

Magnetic fields will rarely be completely uniform. Model XR25 tests the more general case of a uniform field at 2.5 $\mu$G and a random component of equal size, consistent with (although slightly lower than) observational estimates for magnetic field strengths in the diffuse gas (Heiles 1996; Beck 2004b; Han 2006). Giacalone & Jokipii (2007) showed in a two-dimensional numerical experiment that pre-existing perturbations in the inflows can lead to substantial magnetic field amplification due to a rippling of the shockfront and subsequent field-line stretching. We observe a similar effect in model XR25, although our Mach numbers are substantially lower (their study addressed the propagation of a supernova shock front). Hennebelle et al. (2008) perturb the velocities of the inflows and find only a modest increase of the field strength. Clearly, the initially tangled field leads to rather different dynamics in the forming cloud (Figures 1, 6).

Models X25 and X50 demonstrate that not only the field orientation will play a role during cloud formation (see model Y05), but also the field strength, since all the instabilities involved have threshold limits for the field strength—at least in two dimensions. It might well be that the stronger field in model X50 suppressing the formation of filaments could be offset by higher inflow speeds or substructure in the flows. This remains to be studied.

4.2. Turbulence and Thermal States

Fields aligned with the inflows tend to suppress the NTSI, and thus lead to an approximate equipartition between the spatial components of the kinetic energy in the cold and in the thermally unstable gas (Figure 4, bottom couple of rows). For comparison, the hydrodynamical model H has the bulk of the kinetic energy in the (flow-aligned) x-component. Magnetic fields may play an important role to isotropize highly directional flows. Thus, searching for observational signatures of flow-driven cloud formation should focus on the warm, diffuse gas phase, since the inflow signature will be erased in the cold dense gas.

Fractions of thermally unstable gas (Figure 8) for flow-aligned fields (models X50, X25) are lower than values observed
for diffuse CNM clouds (Heiles & Troland 2003). A lateral field component results in a thermally unstable gas fraction of ≈ 50%, consistent with observations. Based on these findings, one could feel tempted to extend the above argument about the selection effect introduced by magnetic fields: not only could magnetic fields control the locations of molecular cloud formation, but they also could lead to “failed” molecular clouds, i.e., diffuse atomic hydrogen clouds, if there is a non-negligible field component perpendicular to the sweeping-up flow (see also Inoue & Inutsuka 2008) for a similar argument based on two-dimensional simulations.

4.3. Ordered versus Random Component

Another observational constraint is given by the ratio of the ordered over the unordered (or turbulent) field component. The observational evidence points to the components being of similar magnitude (e.g., Heiles 1996; Beck 2004b; Beck 2004a; Han 2006; see also discussion in HT05). A direct comparison to our models is hampered by the fact that in order to see the varying component, sufficiently large scales need to be addressed, which is why HT05 argue that their observed median field strength of 6 μG should be identified with the total magnetic field strength. Likewise, it is not obvious that the components should be of equal magnitude locally everywhere. Bearing this limitation in mind, it is clear from Figure 7 that only for models X25 and Y05 the components are comparable.

4.4. Gravity

We deliberately left out self-gravity in our simulations, in order to get a clearer view of the role of magnetic fields during the early cloud formation phase. Thus, our clouds are only confined by the ram pressure of the inflows, and at later stages, the dynamics of the clouds are probably underestimated since gravity as a source of turbulence is missing (e.g., Field et al. 2008). As a result of the restricted physics, a comparison of our models with observations is only meaningful for models where gravity is not expected to play a role, i.e., for model Y05 addressing the formation of diffuse H I clouds. For all other models, we expect gravity to be relevant during the cloud formation process (Heitsch & Hartmann 2008).

5. SUMMARY

Extending our previous work and complementing a model by Hennebelle et al. (2008; see also Banerjee et al. 2008), we study the role of magnetic field strength and orientation on the process of flow-driven cloud formation. Our models include the usual heating and cooling effects, allowing rapid dissipation. It remains to be seen how nonideal MHD processes affect the structure formation during the buildup of the clouds (e.g., Inoue & Inutsuka 2008).

We thank the referee for a critical and very helpful report. Computations were performed at the National Center for Supercomputing Applications (AST 060034) and on the local PC cluster Star, perfectly maintained and administered by J. Hallum & R. Bonser. F.H. is supported by the University of Michigan and NSF grant AST 0807305. This work has made use of NASA’s Astrophysics Data System.

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