MAGNETIC FIELDS AND GALACTIC STAR FORMATION RATES

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ABSTRACT

The regulation of galactic-scale star formation rates (SFRs) is a basic problem for theories of galaxy formation and evolution: which processes are responsible for making observed star formation rates so inefficient compared to maximal rates of gas content divided by dynamical timescale? Here we study the effect of magnetic fields of different strengths on the evolution of giant molecular clouds (GMCs) within a kiloparsec patch of a disk galaxy and resolving scales down to \( \approx 0.5 \) pc. Including an empirically motivated prescription for star formation from dense gas \((n_H > 10^5 \text{ cm}^{-3})\) at an efficiency of 2\% per local free-fall time, we derive the amount of suppression of star formation by magnetic fields compared to the nonmagnetized case. We find GMC fragmentation, dense clump formation, and SFR can be significantly affected by the inclusion of magnetic fields, especially in our strongest investigated \( B \)-field case of 80 \( \mu \)G. However, our chosen kiloparsec-scale region, extracted from a global galaxy simulation, happens to contain a starbursting cloud complex that is only modestly affected by these magnetic fields and likely requires internal star formation feedback to regulate its SFR.

Key words: galaxies: ISM – galaxies: star clusters: general – ISM: clouds – ISM: structure – methods: numerical – stars: formation

1. INTRODUCTION

Understanding and thus predicting the star formation rate (SFR) that results from a galactic disk of given local properties, such as gas mass surface density, \( \Sigma_g \), and orbital timescale, is a necessary foundation on which to build theories of galaxy evolution. Global and kiloparsec-scale correlations between star formation activity, gas content, and galactic dynamical properties have been observed (Kennicutt & Evans 2012). In molecular-rich regions of normal disk galaxies, overall SFRs are relatively slow and inefficient, i.e., a small fraction, \( \epsilon_{\text{orb}} \approx 0.04 \), of total gas is converted to stars every local galactic orbital time (Suwannajak et al. 2014). Most star formation is concentrated within \( \sim 1 \text{–}10 \) pc-scale regions within giant molecular clouds (GMCs), but even here star formation appears to be inefficient, with similarly small fractions, \( \epsilon_{\text{ff}} \approx 0.01 \text{–}0.05 \), of total gas forming stars every local free-fall time, \( t_{\text{ff}} \equiv (3\pi/[32G\rho])^{1/2} \), where \( \rho \) is gas density (Krumholz & Tan 2007; Da Rio et al. 2014). Low efficiencies of star formation may be the result of some combination of turbulence (Padoan et al. 2014), magnetic fields (McKee 1989; Tassis & Mouschovias 2004), and star formation feedback (Krumholz et al. 2014). Here we consider the effects of magnetic fields on the evolution, collapse, and SFR of a turbulent, shearing, kiloparsec-scale region of a galactic disk, extracted from the global galaxy simulation of Tasker & Tan (2009, hereafter TT09).

Van Loo et al. (2013, hereafter Paper I) showed that in the limit of purely hydrodynamic evolution with no star formation feedback, GMCs forming, evolving, and collapsing in this same kiloparsec-scale environment produce too much high density gas and, hence, the SFR is too high. Additional processes are needed to provide extra support to or disruption of the GMCs. One such process may be supported by magnetic fields. Observations show that clouds such as, e.g., Taurus and Oph, are threaded by strong \( B \)-fields (e.g., Heiles 2000; Goldsmith et al. 2008) and that the field is connected on larger scales to galactic fields (Li & Henning 2011). The average solar-neighborhood Galactic magnetic field is \( 6 \pm 2 \mu \)G (Beck 2001). Crutcher et al. (2010) argue for a random distribution of field strengths from 0 to \( B_{\text{max}} \) with \( B_{\text{max}} = 10 \mu \)G in low density gas \((n_H < 300 \text{ cm}^{-3})\) and \( B_{\text{max}} = 30(3n_H/300 \text{ cm}^{-3})^{0.65} \) at higher densities. Dynamo amplification to equipartition values is a natural expectation, which has also been seen in numerical simulations (e.g., Wang & Abel 2009; Pakmor & Springel 2013). The magnitude and direction of the \( B \)-field may play an important role in the formation of molecular clouds that are forming from compression of more diffuse atomic gas (Heitsch et al. 2009; van Loo et al. 2010). By potentially stabilizing and supporting GMCs, they may increase cloud lifetimes to the point that other processes such as GMC collisions (Tan 2000) or spiral arm passage (Bonnell et al. 2013) become important.

Here, we extend the model presented in Paper I to include \( B \)-fields, varying their strength to investigate the effect on GMC evolution, especially the amount of high-density clump gas and SFR. Section 2 describes the numerical model, Section 3 presents the results, and Section 4 summarizes and discusses their implications.

2. NUMERICAL MODEL

We start with the same initial conditions as Paper I, i.e., a kiloparsec-sized box at 4.25 kpc from the galactic center extracted from the TT09 simulation. We include the same physical processes, i.e., heating/cooling functions developed in Paper I, and adopt a static background potential yielding flat rotation curve of 200 km s\(^{-1}\). As the TT09 simulation is nonmagnetic, no self-consistent initial magnetic field configuration is available. Therefore, for simplicity, we thread the domain with uniform \( B \)-field along the shearing direction, i.e.,
representing star clusters or sub-clusters of minimum mass $M_D = 100 M_\odot$, to form. These particles are created when the density within a cell exceeds a star formation threshold value of $n_{H, sf} = 10^3 \text{cm}^{-3}$. We assume a local SFR that converts a fraction, $\epsilon_\text{sf} = 0.02$, of gas above the threshold density into stars per local free-fall time (Krumholz & Tan 2007). No mass-to-flux ratio criterion is included, so magnetically-subcritical cells are also able to form stars, with necessary flux redistribution assumed to be occurring at sub-grid scales. Particle motions are calculated by using the gravitational field interpolated from the grid to the particle positions in the equation of motion. The mass of the particles is included when solving the Poisson equation.

3. RESULTS

3.1. Cloud Structure and Fragmentation

Figure 1 shows mass surface densities and temperatures within the numerical domain for models with different initial magnetic field strengths. The pure hydrodynamical model has a very fragmented structure, which becomes smoother as magnetic field strength increases. Significant differences are also seen in the temperature distributions, which are the result of different gas densities (and thus different heating/cooling rates and equilibrium temperatures) and also different amounts of shock heating from large scale flows and accretion heating from dense clump formation. Figure 2 shows zoom-ins of two selected regions, to illustrate more clearly the effects of magnetic field strength on resulting gas structures. Differences in star formation activity are discussed below (Section 3.4).

The fragmentation can be quantified by counting the number of separate clouds that form after 10 Myr of evolution. As in Paper I, we assume a threshold density of $n_H = 100 \text{ cm}^{-3}$ to define gas that is part of molecular “cloud” structures. For simplicity, all connected cells are counted as a single cloud. Using this routine, we find 287, 134, and 28 clouds in the 0, 10, and 80 $\mu$G models, respectively. The mean [median] cloud masses are $4.0 \times 10^5 [27] M_\odot$ for 0 $\mu$G, $7.3 \times 10^4 [100] M_\odot$ for 10 $\mu$G, and $3.1 \times 10^5 [5.0 \times 10^4] M_\odot$ for 80 $\mu$G. Most clouds forming in the 0 and 10 $\mu$G models are thus of very low mass. As expected, increasing the magnetic field strength has a major impact on the fragmentation of the initial GMCs. The magnetic critical mass of spherical clouds, $M_B = 16.2 (B/10 \mu G)^{8/3} (n_H/1000 \text{ cm}^{-3})^{-2}$ (Bertoldi & McKee 1992), shows we expect a factor of $\sim 500$ change in typical cloud mass comparing the 10 and 80 $\mu$G cases, which is seen in the median cloud masses.

In Figures 1 and 2 we also see that the magnetic field is more distorted by gas motions in Region 1 than Region 2. In the 10 $\mu$G run, filaments predominantly lie parallel or perpendicular to field orientation. On $\sim 100$ pc scales, the 80 $\mu$G fields are hardly affected by the cloud motions, but do become more distorted and disordered in regions of high star formation activity.

3.2. Column and Volume Density Distributions

We also quantify ISM structure by examining the probability distribution functions (PDFs) of $\Sigma_\nu$ (as viewed from above the disk) and number density of H nuclei, $n_H$. Figure 3 shows these
quantities weighted by area/volume (top row) and by mass (bottom row). The $\Sigma_g$ PDF is a directly observable feature of clouds and galaxies, while the volume density PDF needs to be reconstructed using different techniques (e.g., Kainulainen et al. 2014).

The $\Sigma_g$ PDFs show the typical combination of a log-normal with power-law tail at high surface densities (e.g., Kainulainen et al. 2009). The transition occurs around $10^{-2} \text{ g cm}^{-2}$, corresponding roughly to the minimum $\Sigma_g$ of regions containing “cloud” (GMC) gas, which is essentially all part of self-gravitating structures. There is variation from region to region, with Region 1 having its log-normal peaking at higher $\Sigma_g$. The shape of the power-law distribution differs only slightly between these individual regions, roughly scaling as $\Sigma_g^{-\alpha_{\Sigma_g,PDF}}$ with $\alpha_{\Sigma_g,PDF} \approx 1$ for the area-weighted PDF, and thus relatively flat slopes of the mass-weighted distributions.

Figure 1. Logarithmic mass surface density (top) and logarithmic mass-weighted temperature (bottom) integrated along the $z$-axis for (from left to right): initial conditions ($t = 0$); final conditions ($t = 10$ Myr) with $B = 0, 10, \text{ and } 80 \mu\text{G}$. Lines indicate projected direction of mass-weighted magnetic field and black dots show positions of star cluster particles. Boxes in the second top panel show different “region” (yellow) and “cloud” (white) selections.

Figure 2. Mass surface densities of Regions 1 (top) and 2 (bottom) for 0 (left), 10 (middle), and 80 $\mu\text{G}$ (right). Black dots show star cluster particles, each representing $100 \, M_\odot$ of stars, while lines indicate direction of mass-weighted magnetic field.
normalization at given $\Sigma_g$ is several times higher in Region 1 than Region 2, i.e., the former has a higher dense gas mass fraction. This also correlates with its more fragmented morphology and larger SFR (below).

There are only modest differences seen in the PDFs as a function of magnetic field strength (although note the large dynamic range in the figures). At higher $\Sigma_g$, these are more clearly seen in Region 2, which also shows the greatest effect from $B$-field strength on its degree of fragmentation and SFR (below).

Comparing to observations, somewhat steeper indices, i.e., $\alpha_{\Sigma_g,PDF} \approx 1.33 - 3.65$, have been reported in dust-emission-derived $\Sigma_g$ PDFs by Schneider et al. (2014). We note that some extinction-based studies find PDFs that can be fit by a single log-normal up to $\Sigma \approx 0.5 \text{ g cm}^{-2}$ (Butler et al. 2014a). Note, these observations are derived from “in-plane” higher-resolution views of clouds, in contrast to the “top-down” views of the galactic plane from the simulations. Direct observational constraints of top-down views are expected to be able to achieved with high angular resolution observations of nearby galactic disks, e.g., with ALMA.

Volume density PDFs in the simulations show similar trends as the $\Sigma_g$ PDFs, with Region 1 having a larger fraction of gas at higher densities. For $n_H > 100 \text{ cm}^{-3}$, i.e., the cloud gas, the distributions can be reasonably well approximated with single power laws up to $\sim 10^5 \text{ cm}^{-3}$ with power law index of $\approx -1$.

### 3.3. Evolution of Dense Gas Mass Fraction SFRs

Here we consider the time evolution of cloud ($n_H > 100 \text{ cm}^{-3}$) and clump ($n_H > 10^5 \text{ cm}^{-3}$) mass fractions over the 10 Myr timescale of the simulations (Figure 4). For the whole kiloparsec-sized region, cloud mass fractions start from relatively high values, $\approx 0.6$, inherited from the TT09 simulation. Over 10 Myr, they show a moderate decline, partly because of the build up a mass fraction in stars, and partly in the magnetized cases from expansion of cloud envelopes due to the introduced magnetic pressure. Clump mass fractions grow to peak values of $\sim 0.05 - 0.1$, with smaller peak values reached more slowly as the $B$-field is increased. Since stars are only allowed to form from clump gas, SFR evolution closely tracks clump mass fraction evolution, although it exhibits more stochasticity. At late times the different models appear to converge in their clump mass fractions and SFRs, perhaps due to the exhaustion of most of the initially unstable gas via star formation.

Regions 1 and 2 follow similar trends. Indeed Region 1’s area of $0.16 \text{ kpc}^2$ contains large fractions of the clump mass and star formation of the whole kiloparsec region. Region 2...
starts with gas structures that are somewhat easier to stabilize with magnetic fields (at least in directions perpendicular to the initial y-direction field orientation), so larger differences are seen in clump and SFR evolution as field strength is increased. Region 1 contains $3 \times$ as much cloud gas as Region 2. It contains two GMCs in the process of merging, and the resulting cloud has significant kinetic energy. The magnetic field therefore plays a minor role in this case. The overall SFR surface densities are about $10 \times$ larger in Region 1 compared to Region 2.

Some caveats are in order. First, the formation of clumps is a response to simulation initial conditions, where dense, self-gravitating clouds are allowed to collapse to high densities as the resolution is suddenly increased. Second, once formed, star particles contribute gravitationally, but stellar feedback, implementation of which is much more uncertain and numerically challenging, is not yet included in the simulation.

### 3.4. Magnetic Fields and Average SFRs

The detailed time history of clump and star formation is sensitive to the choice of initial conditions. It is therefore useful to compare the SFR averaged over the full 10 Myr evolution to the observations since these are also averaged over $\sim 10$ Myr. Here we consider the absolute and relative average SFRs that are seen in the simulations on the kiloparsec, “region,” and “cloud” (i.e., 100 pc) scales.

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Figure 4. Time evolution of mass fraction (left) in clouds (solid), dense clumps (dashed), and star cluster particles (dotted) and SFR per unit disk area (right) for different values of magnetic field, i.e., 0 (black), 10 (blue), and 80 $\mu$G (red). Top panel is for full domain, middle for Region 1, and bottom for Region 2.
4. SUMMARY AND DISCUSSION

We have studied the effects of magnetic fields on molecular clouds extracted from a global galaxy simulation, especially for cloud structure and SFRs. Magnetic fields suppress fragmentation, as expected from consideration of the magnetic critical mass. Their effects on $\Sigma_\mathrm{g}$ and $n_\mathrm{H}$ PDFs are more modest.

In the context of models of star formation from gas above a threshold density ($n_\mathrm{H} \geq 10^5 \text{ cm}^{-3}$), we find that on the largest kiloparsec-scale, average SFRs are only modestly suppressed by magnetic fields. However, this is due to the presence of a starbursting region (Region 1) in the simulation domain. Considering other regions, including down to “GMC”-scales of $\sim 100$ pc, we find a variety of $\Sigma_{\text{SFRs}}$, with values quite similar to those of some Galactic GMCs. Average suppression factors of $\epsilon_B = 0.76, 0.54$ for $B = 10, 80 \mu G$ compared to the nonmagnetized case are seen in the clouds, but in some cases there can be much more dramatic effects, including complete suppression in one cloud.

As a numerical experiment, this study highlights several important aspects, including issues of $B$-field initialization when overdense structures are already present in initial conditions. Stochastic effects are important, i.e., variation in behavior of individual GMCs, and kiloparsec-scale SFRs can be influenced by a single GMC complex. A sub-grid model for star formation is needed: here via a chosen threshold density and an empirically motivated efficiency per local free-fall time, $\epsilon_B = 0.02$. Such low efficiencies may require the effects of local star formation feedback, like protostellar outflows, to maintain turbulence and prolong star cluster formation (Nakamura & Li 2007), and/or they may result from the influence of magnetic fields themselves. Note, we have not included magnetic field effects on the star formation sub-grid model, rather keeping its empirically based parameters fixed for simplicity. There is scope in future work for exploring magnetic sub-grid star formation models, where cell mass-to-flux ratio is also an input, which should lead to a more natural threshold criterion for star formation activity.

Other effects of local star formation feedback, such as stellar winds, ionization, and supernovae, have not yet been included in these simulations, but are expected to act to further reduce SFRs. To disentangle the relative importance of these effects and of magnetic fields will require testing many properties of the simulated clouds and young stellar populations against observed systems (e.g., Butler et al. 2014b).

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