Anchoring Magnetic Fields in Turbulent Molecular Clouds. II. From 0.1 to 0.01 pc

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Abstract

We compared the magnetic field directions inferred from polarimetry data obtained from 100 pc scale inter-cloud media (ICM) and from subparsec scale molecular cloud cores. The highly correlated result led us to conclude that cloud turbulence must be sub-Alfvénic. Here we extend the study with 0.01 pc cores observed by interferometers. The inferred field directions at this scale significantly deviate from that of the surrounding ICM. An obvious question to ask is whether this high-resolution result contradicts the sub-Alfvénic picture concluded earlier. We performed MHD simulations of a slightly super-critical (magnetic criticality = 2) clouds with Alfvénic Mach number $M_A = 0.63$ ($M_A \equiv \langle \sigma_V/V_A \rangle$, where $\sigma_V$ and $V_A$ are, respectively, local 3D velocity dispersion and Alfvén velocity; ...) means the average within the entire simulated volume; e.g., Burkhart et al. 2009), which can reproduce the Paper I results, and observed the development toward smaller scales. Interestingly, all subregions hosting cores with $n_{H_2} > 10^5/cc$ (the typical density observed by interferometers) possess $M_A = 2$–3. Not too surprisingly, these slightly super-Alfvénic cores result in $B$-field orientation offsets comparable to the interferometer observations. The result suggests that gravity can concentrate (and maybe also contribute to, which requires further study to confirm) turbulent energy and create slightly super-Alfvénic cores out of sub-Alfvénic clouds. The results of our simulations also agree with the observed velocity-scale, mass-scale, and field-density relations.

Key words: galaxies: star formation – ISM: clouds – ISM: magnetic fields – polarization – turbulence

1. Introduction

The critical role played by turbulence in star formation has been solidly established in the past two decades; see, for example, the review by McKeen & Ostriker (2007). Their review noted that cloud magnetic fields ($B$-fields) are “not too weak, however,” based on the ordered $B$-fields mapped from three clouds (Li et al. 2006). We (in Paper I) further confirmed this picture of ordered cloud fields by showing the field-direction correlation between 25 cloud cores (1–0.1 pc) and their surrounding inter-cloud media (ICM ~100 pc). The offsets between the core and ICM fields are shown in Figure 1 (black). Afterward, more evidence of dynamically important cloud $B$-fields have been detected; see our PPVI review (Li et al. 2014).

Recent interferometer (SMA and CARMA) surveys showed that the core-ICM correlation in the $B$-field direction does not seem to be present within small cores at ~0.01 pc (Hull et al. 2014; Zhang et al. 2014). This raises several questions: (1) is the situation the same for the cores collected in Paper I? (2) If so, what does the situation imply? Does it mean that the turbulence changes from sub-Alfvénic, the conclusion from Paper I, to super-Alfvénic at smaller scales? To answer question (1), we have collected data from Zhang et al. (2014) and Hull et al. (2014; Z/H14 hereafter) for those cores in Paper I and the result is presented in Section 2, Table 1 and Figure 1. To answer question (2), we have performed sub-Alfvénic molecular cloud simulations to first reproduce the result from Paper I (above 0.1 pc) and then observe the circumstance at scales 0.1–0.01 pc. The results of the simulations are summarized in Section 3, which are compared with observations in Section 4.

2. Extending Paper I to Smaller Scales

The core field data in Paper I are collected by CSO (Dotson et al. 2010) and JCMT (Matthews et al. 2009). The scale is an apparent potential reason for the different field alignment observed by Paper I and the later interferometer surveys (Z/H14). To test this, we extend the study of Paper I to smaller scales using data from Z/H14. The field offsets between Z/H14 and the vicinity ICM (adopted from Paper I) versus core scales is also shown in Figure 1. The polarization data from Z/H14 for each core is propagated to the mean core field direction using Stokes parameters following Paper I. A core scale is defined by the 10%–peak intensity contour and estimated by the average of the contour scales in the R.A. and decl. directions. Indeed, the upper envelope of Figure 1 increases as the scale decreases. Below 0.1 pc, there seems no preference for the ICM field direction; the offsets evenly distribute between 0° and 90°.

3. MHD Simulations

It is suggested in Paper I and later confirmed by others (e.g., Li et al. 2015b) using numerical simulations that the field alignment seen in Paper I is possible only if the turbulence is trans- or sub-Alfvénic. The most straightforward observation we can make here regarding those simulations that already reproduce the result of Paper I is how the field directions will develop with further fragmentation to compare with Figure 1. Hence, we performed a set of 3D MHD simulations of sub-Alfvénic clouds using the ZEUS-MP code (Hayes et al. 2006). We observe the change of $B$-field orientation associated with gas clumps of various scales as seen in Figure 1. The detailed parameters are described in the following section.
The simulations are isothermal (10 K) and start with a uniform density \((1.20 \times 10^{-2} \text{ g cm}^{-3} \text{ or } 300 \text{ H}_2/\text{cc assuming a mean molecular weight of } 2.36)\) and a uniform \(B\)-field (14.4 \(\mu\)G) over a cube with a linear size of 4.8 pc, which is resolved evenly by 960 pixels. The boundary condition is periodic. The ratio of the total mass to the magnetic critical mass \((\Phi/2\pi G^{1/2}, \text{ where } \Phi \text{ is magnetic flux), a.k.a., magnetic criticality, is } 2.\) The simulations proceed in two stages. First, self-gravity is turned off, and the pure solenoidal turbulence is driven at 2.4 pc until the turbulent energy power spectrum is stable. At this point, the sonic Mach number is 5.7 and the overall Alfvénic Mach number, \(M_A \equiv (\sigma_V/\nu_A)\), as conventionally defined in the literature (e.g., Burkhart et al. 2009), is 0.74. This \(M_A\), however, is not observable, as both the Chandrasekar–Fermi and Zeeman methods measure the mean field strength of a targeted volume. To connect simulations with observations, here we define \(M_{\text{A,obs}} \equiv \Sigma_V/V_A\), where \(\Sigma_V\) and \(V_A\) are similar to \(\sigma_V\) and \(\nu_A\) but the density weighted 3D velocity dispersion and Alfvén velocity based on the density weighted mean field strength of the whole volume; \(M_{\text{A,obs}} = 0.92\). The viral parameter, \(5\Sigma_V^2L/6GM\), is 0.51, were \(M\) and \(L\) are, respectively, the total mass and total volume scale. During the second stage, self-gravity is turned on while the turbulence driving continues for another 1 Myr. At the end, the velocity spectrum remains Kolmogorov-type (Figure 3) with an overall \(M_{\text{A,obs}} = 0.84\) and \(M_A = 0.63\). More details about the turbulence driving can be found in the appendix of Otto et al. (2017). The Jeans length is always resolved by at least eight simulation pixels (Truelove et al. 1997). We repeated the simulation three times (Cubes 1, 2, and 3; Table 2) with different random seeds for turbulence generation.

As our goal is to understand observations, we will mainly use \(M_{\text{A,obs}}\) hereafter. Note that, conventionally, only the initial \(M_A\) of a simulation is reported in the literature (e.g., Li et al. 2015b, Mocz et al. 2017), but an initial condition is not comparable with observations. The energy redistributes between gravity, turbulence, and \(B\)-fields as time goes on. Here we report \(M_{\text{A,obs}}\) one million years after gravity is turned on, which is in the same order as the typical cloud age.

### 3.1. Simulation Setup

Figure 1: Core/ICM \(B\)-field offsets against the spatial scales of cores. The black symbols are from the data in Paper I and the red symbols are the interferometer data \((Z/H14).\) Data from Paper I with no interferometer counterparts are shown as hollow circles. The error bars indicate the interquartile ranges (IQRs) of the \(B\)-field orientation distributions. Above \(~0.1 \text{ pc, most of the offsets are smaller than } 45^\circ\) and the upper envelope grows with decreasing scale. Below 0.1 pc, there seems to be no direction preference at all.

### 3.2. Simulation Results

**Overall field–density relation**—As the first look of the simulation result, we simply survey the offset between local field orientation and the initial field direction and study how this offset is related to density (Figure 2, upper panel). For “local” field orientation, we divided the 960\(^3\) pixel cube evenly into 30\(^3\) pixel subcubes and calculated the density weighted mean field direction of each subcube. The reason to use the 30 pixel scale for a subcube is that the turbulent energy is artificially dissipated below 20 pixel scale (Figure 3; which is typical for numerical simulations; see Kritsuk et al. 2011), where the field structures due to turbulence are thus underestimated. The density-offset relation of the \((960/30)^3\) subregions of Cube 1 is shown in Figure 2 (upper panel), where the upper envelope of the offset systematically increases with the density. This is the first indication that our simulations might be able to explain Figure 1, as the upper envelope of Figure 1 also increases with decreasing scales, which implies increasing density.

Also shown in Figure 2 (lower panel) is the field strength against density at the pixel scale in Cube 1. The slope of the upper envelop gradually changes from \(~0.03\) at the lower density \((n_{H_2} < 10^3)\) to \(~0.67\) at the higher density \((n_{H_2} > 10^3)\), which is similar to the \(B–n_{H_2}\) relation observed by Crutcher et al. (2010) with Zeeman measurements.

**Field–density relation of high-density cores**—To study how the field can be further deviated in even higher densities, we
need to zoom-in on even smaller scales, keeping in mind that once getting smaller than the 20 pixel scale, the field offset from our simulations should be treated as the lower limit because the turbulent energy is artificially dissipated (Figure 3).

To ensure a density range that covers both single-dish and interferometer data, we first identify cores with $n_{\text{H}_2} > 10^5$/cc in our simulations; five cores reach this density. For each of these cores and their surrounding regions, contour surfaces of a series of $n_{\text{H}_2}$, as shown in Table 2, are identified. The scale of the volume enclosed by each contour surface is estimated by the cube root of the volume. The mean field direction of each volume is calculated by the density-weighted mean of the field directions at all the pixels within the contour surface. This way, within a core region, density increases with decreasing scale, which imitates the observations in Paper I and Z/H14.

The result of core field orientations is shown in Table 2 and Figure 3, where the 3D offsets are measured from the direction of the uniform field in the initial condition. Figure 3 already looks inspirational, because of the large offset angles at smaller scales. Above 0.1 pc, which are mainly the scales probed by Paper I, the angles are all smaller than 45°. Below 0.1 pc, the offset increases but still within 90°. Again, due to the unrealistic turbulence energy dissipation below the 20 pixel scale, the offsets from below 0.1 pc are just lower limits. Mocz et al. (2017) performed similar simulations with a much higher resolution such that artificial energy dissipation only happens at scales much smaller than 0.01 pc and still they found offsets not excessing 90° at 0.01 pc for $M_A = 1.2$ and even 3.5. However, note that their $M_A$ is defined by the “input” kinetic energy and the initial $B$-field strength; at the snapshot where they measured offsets, the $M_A$ should be significantly lower (see Section 3.1).

Note that the $B-n_{\text{H}_2}$ relation “within each core” in Table 2 is much shallower than a power law with index 0.67 (Crutcher et al. 2010). The index here (~0.3) is closer to the one observed by Li et al. (2015a). Indeed, the $B-n_{\text{H}_2}$ relation of each core
describes the condition within “affiliated structures,” which is comparable to the observation carried out by Li et al. (2015a), but different from Crutcher et al. (2010), where the \( B-n_{\text{H}_2} \) relation is mostly between independent structures. Moreover, the cores in Table 2 extend to density as low as \( n_{\text{H}_2} \sim 10^{3.5} \); if one fits the upper envelope of \( n_{\text{H}_2} \) in Figure 2 (lower panel) with only one power law, the index will be around 0.3. The \( B-n_{\text{H}_2} \) relation in Figure 2 agrees with Li et al. (2015b) and Mocz et al. (2017) in that the 0.67 index is only for \( n_{\text{H}_2} \) well above \( 10^4 \). In other words, if one power law is fitted to a density range involving \( n_{\text{H}_2} < 10^4 \), the index has to be significantly less than 0.67. Yet the 0.67 index from Crutcher et al. (2010) covers \( n_{\text{H}_2} > 300 \). This discrepancy between Zeeman measurements and simulations motivated us to revisit the Bayesian analysis of the Zeeman data (Jiang et al. 2019) and found that the index and the threshold density cannot be reliably derived from the data with large uncertainties in \( n_{\text{H}_2} \).

### 4. Discussion

#### 4.1. Comparison between Simulations and Observations

Our simulations (Figure 3) can be compared with the polarimetry observations (Figure 1) in two different ways. In both cases, we need to get the 2D projections of the field. The properties of the cloud cores resulting from our sub-Alfvénic MHD simulations are shown in Table 2.

| Boundary \( n_{\text{H}_2}/\text{cc} \) | Scale (pc) | \( B \) Offset from Initial Direction (°) | Mean \( n_{\text{H}_2}/\text{cc} \) | Mean \( B \) (\( \mu \text{G} \)) | \( M_{\text{core}} \) |
|-----------------------------------|------------|-------------------------------------|-------------------------------|----------------|----------------|
| Cube1 Core 1                      | 200000     | 0.035                               | 34.9                          | 275552         | 48.37          | 2.12           |
|                                  | 100000     | 0.037                               | 28.0                          | 151554         | 39.35          | 2.67           |
|                                  | 20000      | 0.22                                | 13.3                          | 37255           | 23.30          | 3.83           |
|                                  | 10000      | 0.33                                | 11.5                          | 20738           | 19.53          | 3.95           |
|                                  | 5000       | 0.48                                | 9.3                           | 11283           | 16.57          | 3.82           |
|                                  | 2000       | 0.73                                | 8.9                           | 5338            | 14.60          | 3.16           |
| Core 2                            | 200000     | 0.027                               | 58.6                          | 220300          | 44.74          | 0.92           |
|                                  | 100000     | 0.060                               | 54.3                          | 144254          | 33.42          | 2.40           |
|                                  | 20000      | 0.22                                | 29.4                          | 32944           | 17.97          | 4.22           |
|                                  | 10000      | 0.36                                | 19.3                          | 17696           | 15.80          | 3.78           |
|                                  | 5000       | 0.57                                | 12.9                          | 9524            | 15.29          | 3.00           |
|                                  | 2000       | 0.95                                | 9.1                           | 4376            | 15.17          | 2.12           |
| Core 3                            | 100000     | 0.019                               | 6.2                           | 111272          | 29.66          | 3.41           |
|                                  | 20000      | 0.17                                | 44.4                          | 28798           | 13.35          | 4.20           |
|                                  | 10000      | 0.29                                | 39.6                          | 16754           | 12.52          | 4.02           |
|                                  | 5000       | 0.43                                | 31.4                          | 9766            | 12.26          | 3.64           |
|                                  | 2000       | 0.69                                | 22.2                          | 4620            | 12.80          | 2.74           |
| Cube2 Core 4                      | 200000     | 0.017                               | 47.4                          | 244180          | 82.13          | 1.46           |
|                                  | 100000     | 0.039                               | 31.3                          | 129636          | 50.19          | 1.58           |
|                                  | 20000      | 0.17                                | 23.1                          | 31396           | 21.10          | 3.04           |
|                                  | 10000      | 0.31                                | 18.7                          | 16564           | 16.17          | 3.53           |
|                                  | 5000       | 0.48                                | 12.5                          | 9390            | 14.83          | 3.27           |
|                                  | 2000       | 0.79                                | 7.2                           | 4388            | 14.29          | 2.49           |
| Cube3 Core 5                      | 100000     | 0.0085                              | 81.1                          | 100926          | 28.52          | 0.24           |
|                                  | 20000      | 0.16                                | 4.3                           | 29360           | 14.26          | 5.45           |
|                                  | 10000      | 0.30                                | 6.2                           | 15720           | 12.83          | 5.21           |
|                                  | 5000       | 0.52                                | 4.9                           | 8382            | 12.35          | 4.35           |
|                                  | 2000       | 0.90                                | 4.6                           | 4000            | 12.55          | 3.16           |

Notes.

- \( M_{\text{core}} \) drops when the scale goes below 0.1 pc for all cores. This is due to the limitation of our MHD simulations, which have to artificially damp the turbulence below 0.1 pc; see Figure 3.
- The density–scale \( (l) \) relation derived from these five cores is \( n \sim l^{-0.98 \pm 0.25} \) and the core mass \( \sim (165.1 \pm 25.3) \times l^{1.54 \pm 0.12} M_e \).
- The field strength–density relation derived from these five cores is \( B \sim n^{0.32 \pm 0.08} \); see the discussion in Section 3.2.
Figure 2. $B$-field vs. density in Cube 1. Upper panel: cube 1 is evenly divided into subcubes of $30^3$ pixels, and each data point shows the mean density and the density weighted mean field offset of one subcube. Lower panel: the density is binned into groups with an even width of 200 H$_2$/cc. For all the pixels with densities within one bin, their field strengths are averaged. This is a plot of the averaged field strength vs. the central density of each bin. The reference slopes of 0.03 and 0.67 are shown as the gray solid lines.
angles. Moreover, if a projected angle is obtuse, the supplementary angle should be adopted to imitate the fact that polarization vectors have the 180° ambiguity (headless), and the acute angle is utilized to describe the offset between two polarization vectors (Paper I; Z/H14).

*The overall trend of the field projections*—We bin the 3D angles into three groups—“above 1 pc,” “below 0.1 pc,” and “in between.” Each 3D angle in Figure 3 is projected to 135 directions evenly distributed on a sphere centered at the angle. For each bin, all the projected angles are collected (with obtuse angles replaced by their supplementary ones), and their distribution is also shown in Figure 3. The distributions are comparable to Figure 1: above 0.1 pc, 90% of the projections are below 45°. Below the 0.1 pc scale, even though the 3D offsets here are only the lower limits, the distribution is already close to uniform within 0°–90°. In other words, the large field deviations (relative to the local ICM field orientations) observed by interferometers (Figure 1) do not contradict the idea of an overall sub-Alfvénic cloud ($M_A = 0.63$).

*Reproducing the field directions of affiliated structures*—Besides the overall trend, here we show that the simulation results can also reproduce the observed multiscale field orientations of individual cloud systems. Orion molecular cloud and Cube 1 are used as illustrations because they have more cores (OMC-1, −2, and −3; simulated cores 1, 2, and 3), and each OMC core has at least three submillimeter observations at different scales (Table 1).

In Figure 4, OMC-1, −2, and −3 are isolated, respectively, from Figure 1. The smallest structures are OMC-1 KL NW/SE, OMC-2-FIR3, and OMC-3-MM55/6 (Table 1). For each simulated core, we surveyed all the possible projections. If a projection falls within the error bar of any of the aforementioned five smallest cores and the error bars of its parental structures, we plot this particular projection in Figure 4. Again, even with the underestimated field structures below the 20 pixel scale, there is no problem for the simulation to reproduce the observed field variation over different scales.

### 4.2. The Emergence of Super-Alfvénic Cores

Our MHD simulations can closely reproduce the field offsets from not only Paper I but also Z/H14. To further explore the reason of the field offsets and answer question (2), we study the relation between $n_{H^2}$ and $M_A$. The subcubes under study are evenly distributed within Cube 1 with the smallest separation between two subcube centers equal to 100 pixels (thus there are overlaps between larger subcubes). The result is given in Figure 5, where the $M_{A,obs}$ of cores 1, 2, and 3 at ~100 and ~150 pixel scales are also displayed. While the simulation cube is overall sub-Alfvénic, it can produce dense and super-Alfvénic subcubes and cores. Which is most likely due to the mass (and thus kinetic energy) concentration along the B-fields, that results in local kinetic (turbulent) energy enhancement without magnetic field compression. This anisotropic accretion channeled by B-fields is also observed in other simulations and discussed by Otto et al. (2017). Also, part of the gravitational potential energy may be converted into turbulent energy after the accretion (e.g., Heitsch 2013).

Note that the cores are only slightly super-Alfvénic with $M_{A,obs} \sim 3$ (Figure 5; Table 2). This level of kinetic energy is not enough to randomize the field orientation. The subcubes with $n_{H^2} \sim 10^{13}$ in Figure 2 (upper penal) possess $M_{A,obs} \sim 3$ (Figure 5), but their field direction offsets seldom go beyond...
It will take an $M_A$ an order of magnitude higher to deviate the field to close to 180°, i.e., to randomize the field, at 0.01 pc scale; see, for example, Figure 3 of Mocz et al. (2017). Indeed, the 3D offsets shown in Figure 3 are all within 90°, which is far from random (evenly distributed between 0° and 180°). Note that, however, polarization vectors, which have the ambiguity of 180°, are not able to distinguish between randomness and 3D angles distributed within 0°–90°. Thus one should not conclude a random field based merely on $Z$/H14 data (red in Figure 1).

4.3. Polarization Holes

The trend of increasing field offset with decreasing scale (and thus with increasing density) explains the so-called “polarization holes”—the tendency of the decreasing fraction of submillimeter polarization with growing column density ($N$). In Paper I, we proposed that polarization holes can occur naturally due to more B-field structures along a line of sight with higher $N$, not necessarily due to the lower grain alignment efficiency in high-density regions as suggested in the literature (e.g., Padoan et al. 2001). The fact that $Z$/H14 see higher polarization fraction than Paper I (Tang 2016) supports our proposal. Higher $N$ usually implies a line of sight going through a higher density and thus more $B$-field direction dispersion can be expected (Figure 2). When these richer field structures are not resolved, they will appear as a lower polarization fraction.

5. Summary

We extend the multiscale study of $B$-field directions in Paper I down to the 0.01 pc scale using the data from $Z$/H14. The multiscale field correlation decreases for scales below 0.1 pc. The directionality of $B$-field fields (Paper I) has been understood as that a molecular cloud, as a whole, should be trans- or sub-Alfvénic. Our MHD simulations show that dense cores developing from sub-Alfvénic clouds ($M_{A,\text{obs}} = 0.84$ and $M_A = 0.63$) can be slightly super-Alfvénic ($M_{A,\text{obs}} \sim 3$) to significantly deviate the core fields and thus explain the field offsets observed by interferometers ($Z$/H14), but not enough to randomize the field directions. The simulation results are also consistent with other observations, e.g., $B \propto n^{0.32\pm0.08}$ for affiliated structures (Li et al. 2015a), $B \propto \rho^{0.67}$ for independent high-density structures (Crutcher et al. 2010), $\sigma_V \propto \rho^{0.31}$, the linewidth–size relation.

Figure 4.

Figure 5.

Figure 6.
(Kauffmann et al. 2013) and $M \propto R^{1.54 \pm 0.12}$, the core mass-size relation for core size $R \in [0.1 \, 1] \, \text{pc}$ (Lombardi et al. 2010).

Understanding observations through numerical simulations had become a common practice in modern astronomy. However, we note that $M_A \equiv \sigma_v / v_A$ in the initial condition, the conventional description of turbulence/\textit{B}-field relative importance in a simulation, is not comparable with an observed $M_A$. First, after the turbulence spectrum is stabilized in a simulation, the overall $M_A$ should be significantly lower than the initial condition (Section 3.1). This is because part of the kinetic energy is converted to random B-fields and contributed to the denominator of $M_A$. Second, the observable, $M_{A, \text{obs}} \equiv \Sigma_v / V_A$, the ratio between the density weighted velocity dispersion and the Alfvén velocity of the density weighted mean field, will not be affected by random B-fields and thus higher than the $M_A \equiv \sigma_v / v_A$ (Section 3.1). Third, the localized $M_A$, e.g., $M_A$ of a cloud core, can be significantly different from the overall value of the cloud (Figure 5).

Finally, polarization offsets distributed over $0^\circ - 90^\circ$ (the red data in Figure 1) can be interpreted in two possible ways: (1) the 3D B-field offsets are simply within $90^\circ$; (2) the 3D B-field offsets are over $0^\circ - 180^\circ$, i.e., random, but polarization offsets cannot go beyond $90^\circ$ due to the headless nature of polarization orientations. The interpretation (2), however, requires the turbulence to be highly super-Alfvénic (e.g., $M_A = 35$ in Figure 3 of Mocz et al. 2017), but Li et al. (2015b) showed that simulations with $M_A = 10$ already conflict with the observations in Paper I (the black data in Figure 1).

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