Polarization Properties and Magnetic Field Structures in the High-mass Star-forming Region W51 Observed with ALMA

Patrick M. Koch1, Ya-Wen Tang1, Paul T. P. Ho1,2, Hsi-Wei Yen3, Yu-Nung Su1, and Shigehisa Takakuwa4,1

1 Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan; pmkoch@asiaa.sinica.edu.tw
2 East Asian Observatory (EAO), 660 N. Aohoku Place, University Park, Hilo, HI 96720, USA
3 European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
4 Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065, Japan

Received 2017 April 7; revised 2017 November 27; accepted 2017 December 24; published 2018 March 5

Abstract

We present the first ALMA dust polarization observations toward the high-mass star-forming regions W51 e2, e8, and W51 North in Band 6 (230 GHz) with a resolution of about 0′′ 26 (~5 mpc). Polarized emission in all three sources is clearly detected and resolved. Measured relative polarization levels are between 0.1% and 10%. While the absolute polarization shows complicated structures, the relative polarization displays the typical anticorrelation with Stokes I, although with a large scatter. Inferred magnetic (B) field morphologies are organized and connected. Detailed substructures are resolved, revealing new features such as comet-shaped B-field morphologies in satellite cores, symmetrically converging B-field zones, and possibly streamlined morphologies. The local B-field dispersion shows some anticorrelation with the relative polarization. Moreover, the lowest polarization percentages together with largest dispersions coincide with B-field convergence zones. We put forward sin ω, where ω is the measurable angle between a local B-field orientation and local gravity, as a measure of how effectively the B field can oppose gravity. Maps of sin ω for all three sources show organized structures that suggest a locally varying role of the B field, with some regions where gravity can largely act unaffectedly, possibly in a network of narrow magnetic channels, and other regions where the B field can work maximally against gravity.

Key words: ISM: individual objects: (W51 e2, W51 e8, W51 North) – ISM: magnetic fields – polarization – stars: formation

1. Introduction

The giant molecular cloud W51 is among the most massive star-forming regions in our Galaxy. The W51 complex is further unique as it is located in a region with little foreground and background contamination. Ginsburg (2017) gives a recent observational review. The major regions within W51 are W51 A, B, and C. The two most luminous high-mass protostars, W51 e2 and W51 North, are located in the W51 A region, which has a luminosity equivalent to a star cluster of 5000 to 10,000 M☉. W51 e2 together with e8 is located along a molecular ridge at a parallax distance of about 5.41 kpc (Sato et al. 2010). Parallax measurements toward W51 North yield about 5.1 kpc (Xu et al. 2009). W51 contains an aggregation of H II regions (Westerhout 1958; Martin 1972; Mehringer 1994) and masers detected in several molecular lines (OH in W51 e2, e8, and North, (Etoka et al. 2012); H2O in e2, e8, and North (Genzel et al. 1981; Eisner et al. 2002; Imai et al. 2002); CH3OH in e2, e8, and North (Phillips & van Langevelde 2005; Etoka et al. 2012); and SiO and NH3 in W51 North (Morita et al. 1992; Eisner et al. 2002; Brown & Cragg 1991; Gaume et al. 1993; Henkel et al. 2013). Because W51 A is very bright in the millimeter wavelength range, it has been extensively studied with a variety of molecular lines. Evidence for infall and/or accretion around W51 e2 is reported in Ho & Young (1996), Zhang & Ho (1997), Zhang et al. (1998), Young et al. (1998), and Sollins et al. (2004). A possible rotation with a spin-up motion is discussed in Zhang & Ho (1997) and Zhang et al. (1998). Observations of the hydrogen recombination line H53α led to the interpretation of a rotational ionized accretion flow around the ultra-compact H II region in e2 (Keto & Klaassen 2008). Later higher-resolution observations by Shi et al. (2010a, 2010b) and Goddi et al. (2015, 2016) reveal that e2 fragments into at least two sources, e2-west (a hyper-compact H II region) and e2-east (a hot molecular core), suggesting that the accretion is possibly onto these smaller-scale cores. W51 e8, south of e2 at a projected distance of about 0.3 pc, appears to be in a common larger-scale 0.5 pc envelope together with e2 (Lai et al. 2001; Tang et al. 2009). Infall signatures toward e8 are detected in NH3 (Ho & Young 1996; Zhang & Ho 1997; Zhang et al. 1998) and in CS (Zhang et al. 1998), indicating an early evolutionary stage. Toward W51 North, infall motions are detected in SO2 (Sollins et al. 2004) and CN (Zapata et al. 2008). At a higher angular resolution of 0′′ 4, Zapata et al. (2009) observed an infalling ring-like structure in SO2. The orientation of the molecular outflow traced in SiO (5–4) (150°, Zapata et al. 2009) is similar to the orientation derived from proper motions of H2O masers (105° to 140°, Eisner et al. 2002; Imai et al. 2002). High-resolution continuum observations at 0′′ 7 resolve W51 North into at least four smaller cores along an east–west direction south of the cometary shell-like H II region W51 d (Tang et al. 2013). Recent ALMA observations with a resolution of 1000 au in multiple lines do not reveal unambiguous signatures of infall in e2, e8, or North, but this is likely caused by observational limitations and not a non-existence of infall motion (Ginsburg et al. 2017).

The focus of the present paper is to study the role of the magnetic (B) field with the Atacama Large Millimeter/submillimeter Array (ALMA) at a physical scale of about 5 mpc in W51 e2, e8, and North. To that purpose, we are making use of dust polarization observations. At the densities and scales probed with our resolution in these high-mass
star-forming regions, dust grains are expected to be coupled to the $B$ field, aligned with their shorter axis parallel to the $B$ field. Their emission at (sub-)millimeter wavelength is therefore polarized perpendicular to the $B$-field lines (Cudlip et al. 1982; Hildebrand et al. 1984; Hildebrand 1988; Lazarian 2000; Andersson et al. 2015). This dust alignment is likely made possible through radiative torques (Draine & Weingartner 1996, 1997; Lazarian 2000; Cho & Lazarian 2005; Lazarian & Hoang 2007; Hoang & Lazarian 2016).

The W51 e2/e8 ridge has been the focus of dust polarization observations before, with the aim to map and study the $B$ field. Observations made with the Berkeley-Illinois-Maryland-Association (BIMA) radio telescope array at 1.3 mm with a resolution of $\theta \sim 3''$ show an elongated one-parsec-long envelope around e2/e8 with the $B$ field mostly oriented perpendicular to the longer axis of the envelope (Lai et al. 2001). At the location of the e2 core, there is noticeably less or no polarization detected with this $\sim 0.1\text{pc}$ resolution. Higher-resolution observations with the Submillimeter Array (SMA) clearly resolved a radial-like pinched $B$-field morphology precisely at the location of e2 and a more stretched morphology in e8 with $\theta \sim 0.7''$ at $870\mu\text{m}$ (Tang et al. 2009). From comparing gravitational force and $B$-field tension and noting that both the e2 and e8 core show signatures of infall, the upper limits for their $B$-field strengths are estimated to be $<19\text{mG}$ (e2) and $<8\text{mG}$ (e8), respectively (Tang et al. 2009). The large-scale $B$ field in the plane of the sky, pervading the $0.5\text{pc}$ envelope, is estimated to be $\sim 1\text{mG}$ from the Chandrasekhar-Fermi (Chandrasekhar & Fermi 1953) method in Lai et al. (2001).

Subsequently, W51 e2 served as a testbed for a newly developed technique—the polarization-intensity gradient method—to measure local magnetic field strengths (Koch et al. 2012a, 2012b). A clear increase in field strengths is measured from $\sim 1\text{mG}$ in the core’s peripheral zones to a central value of about $20\text{mG}$. Etoka et al. (2012) quote a $B$-field strength of $2\sim 7\text{mG}$ from OH masers in e2, which is similar to field strengths measured in other compact H II regions detected through Zeeman observations of OH masers (a few mG up to $\sim 20\text{mG}$; Fish & Reid 2007). An analysis of the local magnetic field-to-gravity force ratio shows a clear drop toward the center of e2, indicating that the $B$ field is largely overwhelmed by gravity in the central region, while the field can still provide resistance (force ratio higher than unity) in the northwestern area (Koch et al. 2012a). An identical picture is seen on larger scales, both in between W51 e2/e8 and W51 North, and in between W51 e2 and e8, with a larger field resistance against gravity in between the cores and gravity dominating at the locations of the cores (Koch et al. 2012b).

W51 North was the target of a systematic study to probe the change in $B$-field morphologies (Tang et al. 2013) from a 3 pc envelope surface layer (JCMT/SCUPOP at $850\mu\text{m}$, Chrysostomou et al. 2002; Matthews et al. 2009) to the parsec-scale molecular cloud probed with the CSO/Hertz at $350\mu\text{m}$ (Dotson et al. 2010) down to the core envelope and core resolved with the SMA at the 0.1 pc scale (Tang et al. 2013). The systematic change from a close-to-uniform larger-scale $B$ field to a symmetric field morphology channeling from North and south down to a pulled-in hourglass-like $B$ field is also reflected in a tightening correlation between emission gradients and field orientations (Tang et al. 2013), which is explained by increasingly dominating gravity over the $B$ field (Koch et al. 2013). This finding was later confirmed in a large 50-source sample with data from the SMA and the CSO in Koch et al. (2014). In W51 North, field-to-gravity force ratios are low (about 0.5) on average, but grow to values higher than unity outside of the core regions (Tang et al. 2013).

This paper is organized as follows. Section 2 describes our ALMA observations. Maps of dust continuum, polarized emission, and $B$-field morphologies are presented in Section 3. We discuss the connection between polarization and $B$-field structures, together with a comparison to larger-scale data of the envelope of W51 e2/e8 and North from the SMA, in Section 4. This section further debates $B$ field versus gravity with a new proposed measure. Summary and conclusion are given in Section 5.

2. Observations

The project was carried out with the ALMA Band 6 receiver in the Early Science phase (Cycle 2, project “2013.1.00994.S”). Observations were made in three execution blocks (EBs) on July 18, 2015. The three EBs were calibrated separately in flux, bandpass, and gain. Polarization calibration was performed after merging the three calibrated EBs following the standard polarization calibration for ALMA. A detailed analysis of the instrumental polarization in Band 6 is given in Nagai et al. (2016), who conclude that linear polarization at a level of $\leq 0.1\%$ is detectable. The array included 38 antennas with (projected) baselines ranging from 13 m to 1492 m. The four baselines were set in FDM mode (3840 channels for 1.875 GHz with a resolution of 488 kHz). The calibration (bandpass, phase, amplitude, and flux) was performed using CASA 6 v.4.5.0. J1924–2914 and J1751+0939 were used for bandpass, and J1922+1530 for phase calibration. With a flux of 0.175 Jy at 232.9 GHz, J1922+1530 also provided the flux scale with the reference flux calibrator Titan. The polarization calibrator was J1924–2914, which was measured to have a polarization fraction of 2.56% and a polarization position angle of $45^\circ$, in agreement with other ALMA measurements. W51 was observed with three separate pointings, with phase centers on e2, e8, and North on $(\alpha, \delta)_{2000} = (19:23:29.14, 14:30:34.00), (19:23:43.90, 14:30:27.00),$ and $(19:23:39.95, 14:31:05.50),$ respectively. The images presented here are with natural weighting, which gives a synthesized beam resolution $\theta \sim 0.07'' \times 0.26''$ with an orientation of $33^\circ$. The sensitivities $(\sigma)$ are $6\text{mJy/beam}$ (e2, e8) and $1.4\text{mJy/beam}$ (North) for Stokes $I$, $0.15\text{mJy/beam}$ (e2, e8), and $0.08\text{mJy/beam}$ (North) for Stokes $Q$, and $0.19\text{mJy/beam}$ (e2, e8) and $0.10\text{mJy/beam}$ (North) for Stokes $U$ (Figures 1 and 2). Since polarization measurements $I_p = \sqrt{Q^2 + U^2} > 0$ have a positive bias (while both $Q$ and $U$ can be negative), we debias in the regime of high signal-to-noise ratio, with $I_p \geq 3\sigma_p$ with $I_p = \sqrt{Q^2 + U^2} - \sigma_{Q,U},$ where $\sigma_Q \sim \sigma_U$ are the noise levels in $Q$ and $U$ (Leahy 1989; Wardle & Kronberg 1974). For all results displayed in this paper, we impose the two simultaneous conditions of having Stokes $I \geq 3\sigma$ and $I_p \geq 3\sigma_p$. Resulting median uncertainties and standard deviations of uncertainties for polarization percentages $p = I_p/I$ are 0.21% and 0.15% for W51 e2, 0.28% and 0.16% for W51 e8, and 0.16% and 0.13% for W51 North. Maximum and minimum uncertainties are 0.50% and 0.02%. Median uncertainties and standard deviations of uncertainties for the orientations of polarization positions are $2\sigma$ and $2\sigma$ for W51 e2, $2\sigma$ and $2\sigma$ for e8, and $3\sigma$ and $2\sigma$ for North. Maximum uncertainties are about $9\%$.

---

5. CASA guide https://casaguides.nrao.edu/index.php/3C286_Polarization.

6. http://casa.nrao.edu/.
Polarization maps of W51 e2, e8, and W51 North with various angular resolutions from ALMA and the SMA. Contours depict the Stokes I dust continuum intensity. Polarization orientations are displayed with segments, with their lengths scaled with polarization percentage \( p = \frac{I_p}{I} \). Contours are 3, 6, 10, 20, 35, 50, 65, 80, 95 ... \( \sigma \), where \( \sigma \) is 75 mJy/beam in panel (a), 60 mJy/beam in panel (b) and (c), 6 mJy/beam in panel (d) and (e), 140 mJy/beam in panel (f), and 90 mJy/beam in panel (g). Contours in panel (h) are identical to those in panels (d) and (e), but \( \sigma \) is 1.4 mJy/beam. Panel (a) and (f): SMA observations with \( \theta \sim 2'' \) at 345 GHz probing larger envelope scales, revealing the connection between W51 e2 and e8 in panel (a) and the W51 North region in panel (f). Panels (b), (c), and (g): SMA observations with \( \theta \sim 0.7'' \) at 345 GHz toward W51 e2 in panel (b), W51 e8 in panel (c) (images adopted from Tang et al. 2009), and W51 North in panel (g) (image adopted from Tang et al. 2013). Panels (d), (e), and (h): ALMA observations in Band 6 at 230 GHz with \( \theta \sim 0.26'' \) toward W51 e2 in panel (d), W51 e8 in panel (e), and W51 North in panel (h). Crosses in panels (a), (b) and (d) mark the known submillimeter sources W51 e2-E, e2-W, e2-NW, and e2-N, counterclockwise around the continuum peak. Pluses in panels (f), (g), and (h) mark the known submillimeter sources SMA1, SMA2, SMA3, and SMA4 from east to west. N1 to N4 label the clearly resolved peaks in the ALMA observations. Blue stars indicate UCHII regions. Synthesized beams for each observation are shown with black filled ellipses. Polarization segments are gridded to and displayed at half of the synthesized beam resolution.
Figure 2. Identical to Figure 1, but with magnetic field orientations shown with red segments. $B$-field orientations are rotated by $90^\circ$ with respect to the detected polarization orientations in Figure 1.
For comparison, we also present new larger-scale SMA maps combining data from the subcompact array configuration (described originally in Tang et al. (2013) for W51 North) and the compact array configuration (described originally in Zhang et al. (2014) for W51 e2, e8, and W51 North). Additionally, unpublished data on W51 e2 and e8 from subcompact array observations are added. The resulting images have $\theta \sim 2'' \times 1''$ with an orientation of $28^\circ$, which captures the envelope scale and the previously unseen connection between W51 e2 and e8 (panels (a) and (f) in Figures 1 and 2).

3. Results

3.1. 230 GHz Dust Continuum

The continuum emission is well detected and resolved at a $0''/26$ resolution toward W51 e2, W51 e8, and W51 North (Figures 1 and 2). The total detected continuum emission at 230 GHz in Stokes $I$ is 4.0, 3.7, and 6.8 Jy for W51 e2, e8, and North, respectively.

The W51 e2 core is resolved into 4 sub-cores (Table 1). The flux densities of these dense cores are determined by two-dimensional Gaussian fits to be 2.54, 1.04, 0.22, and 0.10 Jy for W51 e2-E, e2-W, e2-NW, and e2-N, respectively, and there is faint emission (0.2 Jy) in between these cores. The W51 e2 core has also been resolved at 1.3 mm by Shi et al. (2010a) using the SMA with $\theta \sim 1''/1$. Their reported flux densities are $2.15 \pm 0.12$, $0.62 \pm 0.12$, and $0.73 \pm 0.08$ Jy for W51 e2-E, e2-NW, and e2-N, respectively. Our newly reported flux densities are within the $3\sigma$ uncertainty levels of those in Shi et al. (2010a). We note that this difference can be explained by the coarser angular resolution of the SMA observations with respect to the separations of these sub-cores. In addition, there is no detection at the location of W51 e2-N reported in Shi et al. (2010a) in our ALMA data. Instead, a sub-core is detected in the presented ALMA data $0''/5$ west of W51 e2-N. We attribute this emission to W51 e2-N in Shi et al. (2010a), and hence the nomenclature is kept unchanged. This shift in position is a result of the interferometric filtering effect, where the emission from relatively smooth and extended structures will be filtered out, and the structures revealed by ALMA have fewer artifacts because the uv-coverage is more complete.

The W51 e8 region is resolved into two cores, e8-N and e8-S, with some additional faint emission in the south of e8-S. The flux densities are 2.65 Jy and 0.34 Jy for the e8-N and e8-S core, respectively.

The continuum emission toward the W51 North region shows several cores aligned in an east–west direction. These cores have been resolved and reported in Tang et al. (2013). The SMA2 core is now further resolved into a new core to its southwest (N2) and a likely additional emerging peak to its east (SMA2-E). Hereafter, W51 N1 refers to SMA1, W51 N2 to the newly resolved peak southwest of SMA2, W51 N3 to SMA3, and W51 N4 to SMA4. The flux densities are 2.88, 1.49, 0.96, 0.89, and 0.59 Jy for N1, SMA2-E, N2, N3, and N4, respectively (Table 1).

3.2. Polarization

Polarized emission above $3\sigma$ is seen and resolved with ALMA at 230 GHz in W51 e2, e8, and W51 North (panel (d), (e), and (h) in Figure 1). Polarization holes or depolarization zones in the earlier observations with the SMA at 345 GHz ($\theta \sim 0''/7$, here reproduced from Tang et al. (2009) in panels (b), (c), and (g) in Figure 1) are now resolved with ALMA. It is obvious from Figure 3 that the absolute polarized emission $I_p$ does not simply scale with Stokes $I$. W51 e2, e8, and W51 North show high- and low-emission zones and spots in $I_p$ that appear to have no counterparts in $I$. This is clearly seen in the plots $I_p$ versus $I$ (Figure 13, Appendix) that show no correlation but a broad scatter between these two observables. We note that this joint interpretation of $I$ with $I_p$ assumes that both the total intensity and the polarized signal result from the same structure along the line of sight within a synthesized beam resolution. This means that no significant contamination from background, foreground, or any intervening structures should be present.

W51 e2: Zones of decreasing and minimum polarized emission are centered on e2-W, across e2-E along a northeast–southwest direction, and away from the e2-E emission peak along a narrow straight line toward the northwest (Figure 3). A peak is detected east of e2-E and in between the east and west core. The e2-NW satellite core reveals itself with a stripe of minimum polarization along an east–west direction, a growing signal toward the east and two maxima in the North and south, displaying an almost perfect north–south symmetry. This symmetry is also reflected in the magnetic field morphology (Section 3.5, Figure 2).

W51 e8: Absolute polarized emission peaks are seen west of the e8-N peak, in between e8-N and e8-S, and east of e8-S at the lowest Stokes $I$ emission contour. Zones of minimum polarization appear east of the e8-N peak and to its northwest. Both the northern and southern end of e8-S show low-level absolute polarization.

W51 North: Peaks in absolute polarized emission are detected North and south of the core N2 around R.A. offset 0. To a smaller extent, two additional local maxima are seen North and south of the core N1 around R.A. offset 1.5. The remaining cores and connections in between them are mostly weakly polarized around 1 mJy/beam or less, with a few patches that are slightly more polarized up to about 2 mJy/beam.

Unlike the above absolute polarization, the relative polarization $p = I_p/I$ shows systematic trends where $p$ grows with decreasing Stokes $I$ (Figures 1, 4). This is the typically observed anticorrelation of relative polarization versus Stokes $I$, i.e., $p$ versus $I/I_{\text{max}}$ if normalized by the maximum Stokes $I$ value, as e.g., in Tang et al. (2009). Without any exception, all
cores in W51 e2, e8, and North show local minima in $p$ at their Stokes I emission peaks. Similarly, maximum polarization percentages are always associated with the lowest contours in $I$. Nevertheless, a constant $I$ contour can show a significant variation in relative polarization (Figure 4). This means that symmetries in $I$ are not necessarily preserved in $p$, as is evident in e2-E and N2, for instance. This naturally leads to a scatter in the $p$ versus $I$ correlation. This scatter is relatively broad over almost one order of magnitude (Figure 5). This therefore likely indicates a dependence on additional physical parameters that are not captured in this simple anticorrelation. Polarization percentages extend over two orders of magnitude, ranging from around 0.1% to 10% in all sources (Figure 5). The anticorrelation can be fit with power laws with indices $-1.02$ (e2), $-0.84$ (e8), and $-0.84$ (North). Similar slopes are seen in the larger-scale SMA 345 GHz (850 $\mu$m) data (Section 4.3), in an SMA-BIMA comparison for e2/e8 (Tang et al. 2009), and in a comparison with CSO (at 350 $\mu$m) and JCMT (at 850 $\mu$m) observations for North (Tang et al. 2013). A possible connection between the spatially varying polarization percentage $p$ and the observed $B$-field morphologies is discussed in Section 4.1.

### 3.3. Magnetic Field Morphologies

Magnetic (B) field morphologies are clearly detected, revealing organized, coherent, and connected structures. Furthermore, substructures in and between individual cores and shaped $B$-field morphologies in satellite cores can now be identified (Figure 2). In this section, $B$-field orientations are generated by rotating the originally detected polarization orientations in Figure 1 by 90°. $B$-field segments are all displayed with equal lengths, neglecting information about relative polarization (Section 3.2).

W51 e2: Overall, most of the $B$-field segments are pointing toward the main emission peak e2-E (panel d) in Figure 2. In the closer vicinity of the e2-E peak, the segments are becoming almost radial-like. Overall, the field structure around e2-E

---

**Figure 3.** Polarized emission $I_p$ for e2 (top left), e8 (top right), and North (bottom). The contours are dust continuum with levels as described in Figure 1, and the color scale is in units of mJy/beam for $I_p$. Note that $I_p$ is reproduced from the ALMA maps in Figure 1, and for a better visual impression and display of features, the data are additionally overgridded and shown at five times the synthesized beam resolution. Synthesized beams are shown with black filled ellipses.
resembles a dragged-in morphology. Around e2-W, the field segments in the southwestern peripheral area are bent toward the e2-W emission peak, while the remaining surrounding segments still point toward the main peak e2-E, leaving straight segments along an east–west direction between e2-E and e2-W. This possibly indicates that e2-W is pulled toward the more massive e2-E core. The main core e2-E displays two additional features. First, the previous depolarization stripe along the northeast–southwest direction in the SMA observation (panel (b) in Figure 2) is resolved, clearly showing a continuation of B-field segments that now appear to converge from above and below toward a mid-plane along this stripe. Second, perpendicular to this, B-field segments align along a straight northwest–southeast axis. This is particularly obvious in the northern upper plane with field segments converging symmetrically from both east and west toward this central straight axis. Finally, the satellite core e2-NW appears with a comet- or bow-shock-shaped B-field morphology. This core indicates a pinched field structure in the west and a curved bow-shock structure in the east with a north–south symmetry. These features might suggest that e2-NW is passing through the ambient (lower-density) medium from west to east.

W51 e8: The more elongated e8 structure is clearly detected and further resolved into the main core e8-N and e8-S (panel (e) in Figure 2). The polarization coverage is significantly improved as compared to the earlier SMA map (panel (c) in Figure 2). While the western side of e8-N displays B-field segments that appear oriented toward the emission peak, the eastern and particularly the northeastern side indicate field lines that are bending away, more closely aligning with a north–south axis. The smaller core e8-S indicates a cometary field morphology. Although not as obvious as e2-NW, it shows identical features with possibly pinched field lines in its southern end and more curved comet-shaped segments in the northern part. This is suggestive of e8-S being pulled North toward the more massive e8-N. This impression is further

**Figure 4.** Polarization percentages $p = I_\nu / I$ for e2 (top left), e8 (top right), and North (bottom). The color scale is log($p$). Note: Identical to Figure 3, the data are overgridded and shown at five times the synthesized beam resolution. $p$ is extracted from the ALMA maps in Figure 1, where it is encoded in the lengths of the polarization segments. Synthesized beams are shown with black filled ellipses.
supported by the possibly streamlined $B$-field segments in the lower-density bridge between the northern tip of e8-S and the southern tail of e8-N. This morphology—likely shaped by a streaming motion—might also be present in the northern and northeastern zones of e8-N, possibly indicating that the entire e8 is pulled North toward the more massive e2.

**W51 North:** This region harbors at least six cores, aligned along an east–west axis and almost uniformly spaced. Each core displays an organized magnetic field structure (panel (h) in Figure 2). The two most massive cores—N1 and N2 from east to west around R.A. offsets 1°5 and 0°—both exhibit $B$-field segments oriented toward their emission peaks. While N1 appears with a clearly pinched and complete hourglass $B$-field morphology, symmetric around a northwest–southeast axis, N2 only presents likely dragged-in field lines at its western end. In the east, the field segments appear to open up again, be more straight, and possibly oriented toward the larger and more massive N1. Similar to e2-W and e8-S, this characteristic field morphology might be symptomatic for the less massive core (here, N2) being pulled toward the next more massive gravitational center (N1). In contrast to N1 and N2, N3 around R.A. offset $-2^\circ$ clearly reveals field orientations that are dominantly not oriented toward its emission peak, except in the southwestern zone. Many of the $B$-field segments are largely north–south oriented, but with a twist toward the east. This is particularly noticeable in the eastern extension of N3, which forms a bridge (around R.A. offset $-1^\circ$) to N2 and where another core is probably embedded. This overall bending of the entire group of field segments could again indicate that N3, as a whole, is being dragged to the next more massive N3 to the east, although some segments in the west also show a north–south alignment and some tendency toward the emission peak.

**4. Discussion**

**4.1. Polarization Structures and Magnetic Field Morphologies**

The polarized emission—both absolute and relative to Stokes $I$ (Figures 3 and 4)—is clearly not random but appears organized, although in a nontrivial way. Can this emission be understood together with the plane-of-sky projected $B$-field morphologies? Here, we explore correlations among the observables Stokes $I$, polarized emission $I_p$, polarization...
percentage $p = l_p/l$, and the local $B$-field dispersion $S$. The latter was recently probed on large data sets by Planck (Planck Intermediate Results XIX 2015; Planck Intermediate Results XX 2015) and BLASTPol (Fissel et al. 2016). The local $B$-field dispersion is defined as

$$S(r, r_{\text{disp}}) = \frac{1}{N} \sum_{i=1}^{N} [PA(r) - PA(r + r_{\text{disp}})]^2,$$

where $PA$ is the position angle of an observed $B$-field segment at a location $r$, and $i$ counts neighboring $B$-field segments within an annulus $r_{\text{disp}} \geq |r_{\text{disp},i}|$ centered on $r$. Figure 6 shows $S$-maps, evaluated for $r_{\text{disp}} = 0''2$, which measures the field dispersion in an area slightly larger than the synthesized beam $\theta \sim 0''26$. This means that $S$ captures how much a local field orientation changes with respect to its nearest four and next-nearest four neighbors. $S$ will select zones and display higher values where the $B$ field bends more rapidly or changes orientation abruptly. In W51 e2-E (Figure 6, upper left panel) the northeast–southwest mid-plane, toward which the field segments seem to converge from North and south, is clearly identified with higher dispersion values $S$. Except for this stripe, e2-E shows mostly low values, which is a consequence of its radial-like field morphology. An additional zone with clearly enhanced $S$-values is in the northern low-emission region between e2-E and e2-W. This is again a zone where field segments converge symmetrically from east and west toward a central straight axis (Section 3.3). The $S$-parameter also identifies the western side of the mid-plane in the satellite core e2-NW as a high-dispersion area. Similarly to e2-E, this reflects the mirror-symmetric field structures. The $S$-map for e8-N/S is less prominent (Figure 6, upper right panel). Generally, $B$-field orientations appear to change less abruptly in the west (low values in $S$), while the eastern half shows

Figure 6. Local magnetic field dispersion $S$ (color scale in units of degrees, for radius $r_{\text{disp}} = 0''2$) overlaid on dust Stokes I contours for e2 (top left), e8 (top right), and North (bottom). Note: Identical to the Figures 3 and 4, the data are overgridded for clarity and are shown at five times the synthesized beam resolution. The synthesized beams are shown with black filled ellipses.
higher dispersion values. Similarly to e2-NW, $S$ highlights the southern end of e8-S, where the B field might be locally dragged in, as an enhanced dispersion zone. Equally, the northern end of e8-S, where the curved comet-like field structure is opening up, straightened and possibly pulled toward e8-N, also shows a patch of higher field dispersion. Finally, the possibly converging streaming zone from southeast to the height of e8-N shows up as an elongated stretch with higher $S$-values. W51 North (Figure 6, bottom panel) shows an overall more uniformly low B-field dispersion. Two zones of enhanced dispersion are identified symmetrically around N1, in its southeast and northwest. This coincides with the pinching direction of the hourglass-like B-field. Two additional large-dispersion regions are seen slightly off the peaks of N3 and N4. In summary, in all three regions, W51, e2, e8 and North, the $S$-parameter often captures areas that a visual inspection identifies as magnetic field convergence zones (Section 3.3).

The spatial coincidence between lowest polarization fractions $p$ (Figure 4) and highest dispersions $S$ (Figure 6) is visible in many cores, e.g., the stripe across e2-E and e2-NW, wings on N1, and the peaks and offsets in N3 and N4. Figure 7 shows the local B-field dispersion $S$ as a function of polarization percentage $p$. While a large scatter in $S$ is seen for peak polarizations, the lowest polarization percentages clearly converge toward the highest field dispersions. $S$ appears to be anticorrelated with $p$, with a lower envelope (that traces the minimum polarization as a function of dispersion) and with a scatter that increases with $p$. The lowest polarization occurs at maximum dispersion values, while these are seen across the entire Stokes $I$ range. $S$ therefore appears to be only weakly, if at all, correlated with $I$ (see Figure 13, Appendix). This is observed for all three regions, e2, e8, and North. The drop in polarization $p$ with increasing field dispersion can be interpreted as the cancellation of some polarization signal owing to more rapid changes in the field orientations. Hence, this might indicate that the observed field structures in W51 at a scale of 5 mpc ($\theta \sim 0'' 26$) are not yet resolved at those locations, but underlying more rapidly changing structures within our synthesized beam might be responsible for this anticorrelation. This same explanation holds for the observed anticorrelation between $p$ and Stokes $I$ (Section 3.2 and Figure 13, Appendix), assuming that $I$ is a fair tracer for the gas column density. Alternatively, an intrinsic lower grain
alignment efficiency, due to varying densities and temperatures, might also explain these two anticorrelations. Our findings are in line with recent BLASTPol results for the Vela C molecular cloud (Fissel et al. 2016), where a two-variable power-law empirical model is derived to describe the anticorrelation between $p$ and $S$, and $p$ and column density $N$ on a scale of about 0.5 pc (observed at 500 $\mu$m with a resolution of about 2.5). A decrease of $p$ with growing dispersion $S$ on even larger scales is also noted in Planck Intermediate Results XX (2015). Our observations therefore indicate a continuation of these anticorrelations on large parsec scales down to mpc scales.

Finally, we note that the absolute polarization $I_p$ (Figure 3) and the local field dispersion $S$ (Figure 6)—although scattering in a broad band when comparing entire maps (Figure 13, Appendix)—appear with similar structures in certain regions. In particular, this is the case for e2-E and e2-NW, and e8 N/S, where maximum values in $S$ always reflect minimum $I_p$ values. No overall correlation is probably apparent because small and medium dispersions seem to come with any values in $I_p$. This is especially the case for W51 North. While $S$ versus $I_p$ seems to show a weaker less general correlation than $S$ versus $p$ (Figure 7), the correlation tightens when limited to values around $I_{p,\text{min}}$ and $S_{\text{max}}$. It therefore exactly identifies the magnetic field convergence zones that appear with large $S$, and both a low polarization percentage $p$ and low absolute polarization $I_p$.

### 4.2. Gravity versus Magnetic Field: Local B-field Resistance and Magnetic Channelling

Section 3.3 has presented novel B-field features resolved with ALMA 0°26 observations, namely (1) cometary B-field morphologies in e2-NW and e8-S, (2) convergence zones with symmetrical field structures in e.g., e2-E, and (3) possibly streamlined field morphologies between e.g., e8-S and e8-N, and North of e8-N toward e2. These new features are now starting to give the impression that we see the dynamics of flowing material imprinted on and/or by the magnetic field morphologies. Here, we add quantitative estimates that support the dynamical picture given by these detailed B-field morphologies."

**How important is the magnetic field in, e.g., e2-E, e2-W, and e2-NW? In which cores can it still slow down gravitational infall? Where is the field already overwhelmed by gravity, and might there be even local differences within the same core?**

We start our analysis from an ideal magnetohydrodynamics (MHD) force equation (e.g., Koch et al. 2012a) that identifies the local direction of gravity through $\nabla \phi$ and the direction of the magnetic field tension force through $n_B$. We impose the slight restriction that any change in the orthogonal field component is much smaller than the total field strength, i.e., $\frac{\Delta B}{B} \ll 1$. This will hold for any spatially slowly changing field functions. In return, this then allows us to simplify and combine the magnetic field hydrostatic pressure and the field tension terms.

---

7 On very small scales, this assumption might eventually fail for tangled magnetic fields if neighboring beams show large or abrupt changes in field orientations. There are, however, no indications of this to date from observed field morphologies. The ALMA data presented here also still show smooth and continuous changes in almost all locations. The local field dispersion $S$ (Section 4.1) quantifies this with overall low values.

---

8 Calculating the local direction of gravity is introduced in Koch et al. (2012a). The observed dust emission distribution is assumed to represent the total mass distribution that generates the gravitational potential $\phi$. In order to measure the angle $\omega$, only the direction of the gravitational pull, $\nabla \phi$, is needed, but not its magnitude. The total mass, linked to the dust emission through an a priori unknown dust-to-gass mass ratio, is not needed, and hence it suffices to only consider the dust distribution for this calculation. The resulting local direction of gravity at a specific location is then derived by summing all the surrounding pixelized dust emission weighted by $1/r^2$ along the direction to each pixel, where $r$ is the distance between that location and every surrounding pixel. In other words, every surrounding pixel is treated as a point mass that exerts a gravitational pull on that specific location. The smallest scale that can be taken into account is given by the (synthesized) beam resolution. The largest size scale is defined by the largest distance to any detected emission. We note that larger diffuser scales (emission) are filtered out in ALMA data, but this probably does not significantly affect our results because (1) while it is weak to begin with, this emission is additionally less important because of a growing $1/r^2$ shielding; (2) the larger-scale emission often tends to be more symmetrically distributed, and resulting gravitational pulls can thus largely cancel out.
Equation (2) can then be rewritten as

\[ \rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho |\nabla \phi| g \\
+ \frac{1}{4\pi R} B^2 \sin \omega g + \frac{1}{4\pi R} B^2 \cos \omega n_k. \]

Figure 9 shows \( \sin \omega \)-maps for W51 e2, e8, and North. It is evident that the values are not random, but appear in organized structures that can change with location. \( \sin \omega \) averaged over the entire W51 e2 map is small with 0.40 and a standard deviation of 0.27. This indicates that e2, as an entity, is likely overwhelmed by gravity on the observed scales, with an overall small magnetic field resistance. e2-E displays some field resistance in the east that appears to grow toward the center. An additional zone of a more significant B-field presence is in the North with \( \sin \omega \) of 0.5 or larger. Both zones occur at locations where the detected B-field orientations (panel d in Figure 2) are clearly more misaligned with the close-to-radial gravity directions that result from close-to-circular emission contours of the individual cores. The area with largest B-field resistance (\( \sin \omega \approx 1 \)) is around and North of e2-W. In this zone, the B field appears to be more tangential to the dust emission contours, possibly suggesting a pull toward e2-E, and therefore a B field opposing the local gravitational pull toward the center of e2-W. The
satellite core e2-NW displays a north–south asymmetry with minimum sin Ω values in the North and values close to one in the south. This is opposite to the observed north–south symmetry in the cometary B-field morphology, and in both $I_p$ and $p$ (Figures 2–4). This asymmetry is probably driven by the massive e2-E/e2-W complex that pulls e2-NW toward the south. As a consequence, local gravity directions in the e2-NW core deviate from being simply radial toward its emission peak. This effect is most significant in the south, thus leading to large misalignments $\omega$ between field orientations and gravity.

W51 e8 shows a very similar overall B-field effectiveness to oppose gravity with an average sin Ω value of 0.41 and a standard deviation of 0.29. e8-N dominantly reveals low values of about 0.2–0.5, as expected from the likely pulled-in field morphology in these locations (panel (e) in Figure 2). The exception is the eastern side with values up to one. These highest values coincide with field segments that are more tangential to contours and the possible bending away from e8-N (Section 3.3). Except for a western triangular section with sin Ω $\sim$ 0.7, the elongated bridge between e8-N and e8-S mostly displays low values of about 0.1–0.3. This is in agreement with the visual impression of a streamlined B-field morphology, which is probably driven by the locally dominating gravitational center e8-N. The east–west symmetry in the possibly cometary B-field morphology in e8-S is not completely preserved in sin Ω. The reason likely is that the dominating mass, e8-N, is located off the north–south axis. Overall, e8-S is close to maximum resisting gravity in its center (with sin Ω $\sim$ 1). At its western and eastern sides, local gravity is aligned with the B field, indicating that e8-S can accrete material from the two sides. We note that although it shows maximum B-field effectiveness in the center, this does not yet mean that the B field dominates gravity.

W51 North shows varying sin Ω structures in every core, with an overall average of 0.47 and a standard deviation of 0.30. The most massive eastern core (N1) displays low values around $\sim$0.1 to 0.2 in a fan-like opening along a northeast–southwest axis. This area precisely overlaps with the polar regions of the possible hourglass field structure in this core (panel (h) in Figure 2). The very low values in sin Ω indeed suggest, as expected, that gravitational infall/collapse can easily proceed along this direction, and that the B field is here mostly only channeling material. In contrast to this, along the northwest–southeast axis—where the B field is more strongly pulled in—sin Ω reaches maximum values close to one, indicating maximum field resistance. The next massive core to the west (N2, centered around R.A. offset 0$''$) reveals another fan-like low sin Ω area in the west with gradually growing values at its eastern end. As outlined in Section 3.3, this can explain a scenario where infall/collapse can occur locally in the western zone while the eastern end starts to feel the gravitational pull by the more massive core N1 to the east, leading to a gradual bending of the field lines away from N2. This gradual bending then leads to a transition zone in between N1 and N2 where gravity and field segments are misaligned (hence, high sin Ω values), before they are aligned again in the gravitationally dominated zones in N1. The remaining two cores in the west around R.A. offset $-2''$ (N3) and R.A. offset $-3''$ (N4) display more complicated and finer structures. A possible feature is that low sin Ω values are typically found in the upper (northern) and lower (southern) mid-planes of the cores, while most maximum values appear along an east–west axis. This reflects that many field segments show a prevailing north–south orientation, which means that they are closely aligned with gravity in many places. The exceptions are the mid-planes, in particular the eastern and western ends of N3, the western end of N4, and the connecting bridge between N3 and N2, where the B-field experiences a competition between gravitational pull toward N3 and pull toward N2.

We note that sin Ω is different from the magnetic field-to-gravity force ratio, $\Sigma_B$, in our earlier analyses (Koch et al. 2012a, 2012b, 2013, 2014). $\Sigma_B$ measures the local ratio between magnetic field force and gravity (in a range between zero to larger than one) by solving Equation (2), identifying the local direction of gravity and the field tension in an observed map. In this way, it compares and quantifies, in an absolute sense, the relative importance between magnetic field and gravity. Solving Equation (2) is based on the additional assumption of identifying an observed emission gradient direction with the inertial term in the MHD force equation. Appropriateness and possible uncertainties of this assumption are discussed in detail in Koch et al. (2013). sin Ω does not rely on solving Equation (2). It merely projects the field force onto the local gravity direction, and it is therefore free of the above assumption. Its shortcoming is that it can only capture the zones where gravity clearly dominates the B field, i.e., where the B field is dynamically unimportant (sin Ω $\sim$ 0 or small). For higher values, sin Ω $\sim$ 1, the absolute field strength becomes relevant for a quantitative absolute comparison against gravity. A detailed comparison between sin Ω and $\Sigma_B$, together with maps for the field strength $B$, will be presented in a forthcoming work. An initial comparison shows a close structural resemblance between sin Ω- and $\Sigma_B$-maps. Since projection effects cancel out or are minimum for $\Sigma_B$—because $\Sigma_B$ is the ratio of two forces, the direction of each of which is subject to the same or similar inclination angle (Koch et al. 2012a)—this close resemblance argues for sin Ω being able to distinguish between zones of minimum and maximum B-field effectiveness without any significant bias due to unknown projection effects.

On a final speculative note, we stress that sin Ω is clearly not random. Moreover, within zones of low field effectiveness (low sin Ω values), there are channels with sin Ω $\sim$ 0 (Figure 9). Many of these channels appear in magnetic field convergence zones. In these magnetic channels, gravity can act unpinnedly. If this is the case, this would indicate that along certain directions, infall and collapse can proceed in free-fall time, while in other zones, they are significantly slowed down or even completely brought to a halt. This interpretation is, however, at or already beyond the limit of the current resolution. It needs to be further probed with data of even higher resolution whether this speculative scenario is indeed correct. If that is the case, the existence of a network of magnetic channels might have an interesting implication for the star formation rate. Hypothesizing a channel width of $\sim$0.15 (about half of our synthesized beam, leading to a marginal detection), one such channel from the rim to the center would comprise about 0.4% of the entire volume of a sphere with 2$''$ diameter, such as, e.g., in W51 e2. A network of 10 channels would then reduce the star formation rate to 4%, assuming that the entire mass inside the channels (sin Ω $\sim$ 0) is converted into stars, and that all the material outside (sin Ω large) is held back by the B field. Checking observed star formation rates against
future high-resolution $B$-field structures might hence also provide a test to further probe the sin $\omega$ tool.

4.3. Comparison to Larger Scales: $B$-field and Polarization Properties in the Parsec-scale Envelope

While high-resolution ALMA data make the small-scale dynamics visible in the $B$-field morphologies, a remaining key question is how the larger W51 e2, and the more elongated and filamentary e8 and W51 North, are formed in the first place. To this purpose, we here additionally compare unpublished SMA data on larger scales that also detect the polarized emission on the bridge between e2 and e8, and in the more outer peripheral regions toward e2 and e8 (Figures 1, 2). A detailed analysis of the dynamics along the e2/e8 bridge is presented in P. M. Koch et al. (2018, in preparation).

The W51 e2/e8 complex is connected with a bridge where the $B$-field segments appear to bend away from e8 and become gradually more directed toward e2 (panel a in Figure 2). Beyond a distance of about one beam size from the e2 and e8 peaks, the majority of the $B$-field segments starts to display a prevailing east–west orientation. The outer peripheral zones thus clearly reveal field orientations that are perpendicular to the north–south axis of e2/e8, likely probing accretion scales that are very different from the inner much denser regions where the field structures likely start to be shaped by gravity. The histogram of $B$-field orientations—capturing the larger envelope on a $\sim$0.5 pc scale—reflects this with a peak around $90^\circ$, i.e., east–west orientation (Figure 10, left panel). Histograms for the resolved cores at a $\sim$5 mpc scale spread out over the full range in PA from 0 to $180^\circ$, indicating a change from a single prevailing orientation to a more uniform and broader distribution that stands for a more azimuthally symmetrical field configuration. While e8 is fairly uniform, e2 additionally shows a peak around $30^\circ$ that coincides with the orientation of the magnetic field and core major axis already imprinted on the larger scale (dotted square in panel (a) in Figure 2), about $30^\circ$ off the north–south axis.

W51 North shows a similar scenario. The SMA observations with a coarser resolution of about $2^\circ$ (panel f in Figure 2) show one dominating core in an extended envelope along an east–west direction. At the R.A. of the core, field segments are north–south aligned, perpendicular to the source’s longer axis. Farther to the west, the $B$-field orientations gradually bend and point toward the main peak. This is seen in the histogram with two separate groups around $\sim$0 to $40^\circ$ and around $\sim$120$^\circ$ (Figure 10, right panel). The ALMA data (panel h in Figure 2), resolving the individual cores on a $\sim$5 mpc scale, again show orientations spreading over the full PA range. Their distribution again reflects azimuthally symmetrical field configurations, with one peak around $30^\circ$ that results from the main core that appears to be rotated by $30^\circ$ with respect to the larger-scale north–south orientation.

In conclusion, for both e2/e8 and North, denser cores (e2, e8, and a chain of cores in North) appear to form along an axis perpendicular to the larger envelope-scale $B$ field. The $B$ fields of their most massive cores (e2 and N1) are oriented close to the envelope-scale field, with offsets of about $30^\circ$. However, when further zooming in with higher resolution, the $B$-field configurations are generally much more azimuthally symmetrical, with further substructures that are likely decoupled from the larger-scale $B$ field and governed by their own dynamics. In general, the field configurations seen with the SMA on envelope scales are suggestive of a scenario where the $B$-field channels material from the east and west (W51 e2/e8) and from the North and south (W51 North, Tang et al. 2013) to a mid-plane. The higher resolution SMA and ALMA data indeed confirm that the locations of the denser cores are aligned along a north–south (W51 e2/e8) and east–west (W51 North) axis.

An analysis analogously to that presented in Section 4.1 for the SMA envelope-scale data shows similar trends. The local $B$-field dispersion $S$ (Figure 11) picks up the locations where the field changes from a rather uniform orientation (east–west in e2/e8 and north–south in North) to gravitational pull-in (northern and southern end in e2, southern end in e8, and western end in North). Features in absolute polarization $I_p$ are also seen at this resolution, with two maxima in both e2 and e8 off their Stokes I peak positions, and with one maximum in North, west of its peak (Figure 11). Relative polarization percentages $p = I_p/I$ are—similar to the ALMA data—up to...
about 10%, with maximum values at the lowest Stokes I contours. This also confirms the $p$ versus $I$ anticorrelation on the $\sim 0.5$ pc envelope scale (Figure 12, left panels). The only noticeable difference in this comparison with ALMA is the much more scattered $S$ versus $p$ relation, indicating no correlation between these two observables on this scale in these sources (Figure 12, right panels).

5. Summary and Conclusion

We presented the first ALMA continuum polarization observations toward the high-mass star-forming regions W51 e2, e8, and North in Band 6 (230 GHz) with a resolution of $0''26$. We further propose a diagnostic—the angle $\omega$ between the local magnetic (B) field orientation and the local gravity direction—as a way to assess the effectiveness of the B field to oppose gravitational pull. Our main results are summarized below.

1. Polarization structures. Polarized emission is clearly detected with ALMA across all three sources W51 e2, e8, and North. Polarization holes in the earlier SMA data are resolved, implying that such holes and depolarization zones can be signposts for more detailed or finer underlying B-field structures. The absolute polarized emission $I_p$ shows
complicated structures that do not simply correlate or anticorrelate with total Stokes $I$. Polarization percentages $p$ are measured from about 0.1% to 10%. While all three sources reveal an anticorrelation between $p$ and $I$ with slopes around $-1$, this anticorrelation shows a large scatter of almost an order of magnitude. This suggests additional physics that is not yet captured in this simple anticorrelation. SMA observations with $q \sim 2''$ also show a $p$ versus $I$ anticorrelation with similar slope and range in polarization percentage, but with a possibly smaller scatter.

2. **Magnetic field morphologies.** The $B$-field structures in all three regions are organized, coherent, and connected. Additionally, detailed new substructures are resolved, revealing cometary $B$-field morphologies in satellite cores, convergence zones with symmetrical $B$-field structures, and possibly streamlined $B$-field morphologies. Many of the cores display structures that resemble gravitationally bent or pulled-in field lines at one end of the core, while field lines at the other end of the core appear to be dragged away toward the neighboring next more massive core. This might support a scenario where local collapse can start in a small core while this core as an entity is dragged toward the next larger gravitational center. The larger envelope-scale $B$-field morphologies, captured with the SMA $\theta \sim 2''$ observations, reveal prevailing field orientations perpendicular to the direction of the aligned higher-resolution ALMA cores. The bridge between W51 e2 and e8 reveals field lines that are gradually more bent toward the more massive e2.

3. **Magnetic field dispersion and convergence zones.** Similar to larger-scale observations by Planck and BLASTPol, a connection between the local $B$-field dispersion $S$—capturing by how much the local $B$-field orientation varies with respect to its surrounding—and polarization percentage is also seen in the high-resolution ALMA data. In particular, a close spatial coincidence between lowest polarization percentages $p$ and highest dispersions $S$ is evident in magnetic field convergence zones, where symmetrical $B$-field structures appear to converge from two sides. These convergence zones always also have lowest absolute polarized emission $I_p$. The drop in both $I_p$...
and $p$ toward zones of growing $S$ can be interpreted as the cancellation of polarization signal due to rapidly changing field structures that are still not resolved.

4. **Local magnetic field effectiveness opposing gravity.** The direction of the local $B$-field tension force can be projected onto the local direction of gravity by means of the measurable angle $\omega$ between a $B$-field orientation and local gravity. In this way, $\sin \omega$ measures the fraction of the field tension force that can work against gravity. Maps of $\sin \omega$ for all three sources W51 e2, e8, and North are not random, but present organized patterns. Zones where $\sin \omega$ is small (gravity and $B$ field nearly aligned) indicate that the $B$ field is very ineffective in slowing down gravity. Any motion driven by gravity can proceed with little or almost no obstruction from the $B$ field. For regions with higher $\sin \omega$ values, the absolute field strength and gravity need to be known to quantify the role of the $B$ field. Narrow sectors with $\sin \omega \sim 0$ lead to the speculation of magnetic channeling where infall and collapse could proceed in free-fall time.

This paper makes use of the following ALMA data: ADS/JAO.ALMA##2013.1.00994.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MoST, and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. P.T.P.H. acknowledges support from the Ministry of Science and Technology (MoST) in Taiwan through grant MoST 105-2112-M-001-025-MY3. Y.-W.T. is supported through grant MoST 103-2119-M-001-010-MY2. P.M.K. acknowledges support from MoST 103-2119-M-001-009 and from an Academia Sinica Career Development Award. The authors thank the referee for valuable comments and suggestions that further improved this manuscript.

**Facilities: ALMA, SMA.**

### Appendix

**Possible Correlations**

Figure 13 presents all possible combinations of correlations among the various observables and the derived quantities in the Sections 3 and 4 for W51 e2, e8, and North. Variable degrees of correlations are seen among different combinations of parameters.
Figure 13. All possible correlations among Stokes $I$, absolute polarization $I_p$, polarization percentage $p = I_p/I$, and local B-field dispersion $S$ for W51 e2 (top two rows), e8 (middle two rows), and North (bottom two rows) observed with ALMA.
References

Andersson, B.-G., Lazarian, A., & Vaillancourt, J. E. 2015, ARA&A, 53, 501
Brown, R. D., & Cragg, D. M. 1991, ApJ, 378, 445
Chandrasekhar, S., & Fermi, E. 1953, ApJ, 118, 113
Cho, J., & Lazarian, A. 2005, ApJ, 631, 361
Chrysostomou, A., Aitken, D. K., Jenness, T., et al. 2002, A&A, 385, 1014
Cudlip, W., Fruniss, I., King, K. J., & Jennings, R. E. 1982, MNRAS, 200, 1169
Dotson, J. L., Vaillancourt, J. E., Kirby, L., et al. 2010, ApJS, 186, 406
Draine, B. T., & Weingartner, J. C. 1996, ApJ, 470, 551
Draine, B. T., & Weingartner, J. C. 1997, ApJ, 480, 633
Eisner, J. A., Greenhill, L. J., Hernestein, J. R., Moran, J. M., & Menten, K. M. 2002, ApJ, 569, 334
Etoka, S., Gray, M. D., & Fuller, G. A. 2012, MNRAS, 423, 647
Fisch, V. L., & Reid, M. J. 2007, ApJ, 670, 1159
Fissel, L. M., Ade, P. A. R., Angilé, F. E., et al. 2016, ApJ, 824, 134
Gaume, R. A., Johnstone, K. J., & Wilson, T. L. 1993, ApJ, 417, 645
Genzel, R., Downes, D., Schneper, M. H., et al. 1981, ApJ, 247, 1039
Ginsburg, A. 2017, Published in Star Formation Newsletter, 290 arXiv:1702.06627v1; http://www.ifa.hawaii.edu/users/reipurth/newsletter/newsletter_290.pdf
Ginsburg, A., Goddi, C., Diederik Kruijssen, J. M., et al. 2017, ApJ, 842, 92
Goddi, C., Ginsburg, A., & Zhang, Q. 2016, A&A, 589, A44
Goddi, C., Henkel, C., Zhang, Q., Zapata, L., & Wilson, T. L. 2015, A&A, 573, A109
Henkel, C., Wilson, T. L., Asiri, H., & Mauersberger, R. 2013, A&A, 549, A90
Hildebrand, R. H. 1988, QJRAS, 29, 327
Hildebrand, R. H., Dragovan, M., & Novak, G. 1984, ApJL, 284, L51
Ho, P. T. P., & Young, L. M. 1996, ApJ, 472, 742
Hoang, T., & Lazarian, A. 2016, ApJ, 831, 159H
Imai, H., Watanabe, T., Omodaka, T., et al. 2002, PASJ, 54, 741
Keto, E., & Klaassen, P. 2008, ApJL, 678, L109
Koch, P. M., Tang, Y.-W., & Ho, P. T. P. 2012a, ApJ, 747, 79
Koch, P. M., Tang, Y.-W., & Ho, P. T. P. 2012b, ApJ, 747, 80
Koch, P. M., Tang, Y.-W., & Ho, P. T. P. 2013, ApJ, 757, 77K
Koch, P. M., Tang, Y.-W., Ho, P. T. P., et al. 2014, ApJ, 797, 99
Lai, S.-P., Crutcher, R. M., Girart, J. M., & Rao, R. 2001, ApJ, 561, 864L
Lazarian, A. 2000, ASPC, 215, 69
Lazarian, A., & Hoang, T. 2007, MNRAS, 378, 910
Leahy, P. 1989, VLA Scientific Memoranda (Socorro, NM: VLA), 161
Martin, A. H. M. 1972, MNRAS, 157, 31
Matthews, B. C., McPhee, C. A., Fissel, L. M., & Curran, R. L. 2009, ApJS, 182, 143
Mehringer, D. M. 1994, ApJS, 91, 713
Morita, K.-I., Hasegawa, T., Ukita, N., Okumura, S. K., & Ishiguro, M. 1992, PASJ, 44, 373
Nagai, H., Nakanishi, K., Paladino, R., et al. 2016, ApJ, 824, 132
Phillips, C., & van Langevelde, H. J. 2005, in ASP Conf. Ser. 340, Future Directions in High Resolution Astronomy: The 10th Anniversary of the VLBA, ed. J. D. Romney & M. J. Reid (San Francisco, CA: ASP), 342
Planck Intermediate Results XIX 2015, A&A, 576, A104
Planck Intermediate Results XX 2015, A&A, 576, A105
Sato, M., Reid, M. J., Brunthaler, A., & Menten, K. M. 2010, ApJ, 720, 1055
Shi, H., Zhao, J.-H., & Han, J. L. 2010a, ApJL, 718, L181
Shi, H., Zhao, J.-H., & Han, J. L. 2010b, ApJ, 710, 843
Sollins, P. K., Zhang, Q., & Ho, P. T. P. 2004, ApJ, 606, 943
Tang, Y.-W., Ho, P. T. P., Koch, P. M., et al. 2009, ApJ, 700, 251
Tang, Y.-W., Ho, P. T. P., Koch, P. M., Guilloteau, S., & Dutrey, A. 2013, ApJ, 763, 135
Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249
Westerhout, G. 1958, BAN, 14, 215
Xu, Y., Reid, M. J., Menten, K. M., et al. 2009, ApJ, 693, 413
Young, L. M., Keto, E., & Ho, P. T. P. 1998, ApJ, 507, 270
Zapata, L. A., Ho, P. T. P., Schilke, P., et al. 2009, ApJL, 698, 1422
Zapata, L. A., Palau, A., Ho, P. T. P., et al. 2008, A&A, 479, L25
Zhang, Q., & Ho, P. T. P. 1997, ApJ, 488, 241
Zhang, Q., Ho, P. T. P., & Ohashi, N. 1998, ApJ, 494, 636
Zhang, Q., Qiu, K., Girart, J. M., et al. 2014, ApJ, 779, 116