INTERFEROMETRIC UPPER LIMITS ON MILLIMETER POLARIZATION OF THE DISKS AROUND DG Tau, GM Aur, AND MWC 480

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ABSTRACT

Millimeter-wavelength polarization measurements offer a promising method for probing the geometry of magnetic fields in circumstellar disks. Single dish observations and theoretical work have hinted that magnetic field geometries might be predominantly toroidal, and that disks should exhibit millimeter polarization fractions of 2%–3%. While subsequent work has not confirmed these high polarization fractions, either the wavelength of observation or the target sources differed from the original observations. Here we present new polarimetric observations of three nearby circumstellar disks at 2\arcsec resolution with the Submillimeter Array and the Combined Array for Research in Millimeter Astronomy. We reobserve GM Aur and DG Tau, the systems in which millimeter polarization detections have been claimed. Despite higher resolution and sensitivity at wavelengths similar to the previous observations, the new observations do not show significant polarization. We also add observations of a new HAeBe system, MWC 480. These observations demonstrate that a very low (\leq 0.5%) polarization fraction is probably common at large (\geq 100 AU) scales in bright circumstellar disks. We suggest that high-resolution observations may be worthwhile to probe magnetic field structure on linear distances smaller than the disk scale height, as well as in regions closer to the star that may have larger MRI-induced magnetic field strengths.

Key words: magnetic fields – polarization – protoplanetary disks – stars: formation – stars: individual (DG Tau, GM Aur, MWC 480)

Online-only material: color figures

1. INTRODUCTION

Magnetic fields are frequently invoked in theories of star and planet formation; Königl & Salmeron (2011) provide a thorough review of the central role of fields in the formation and evolution of circumstellar disks. While some observations find hourglass-shaped magnetic field geometries in very young star-forming regions, which indicates that magnetic fields play a key role in the early formation of circumstellar disks (e.g., Girart et al. 2006), there are few observational constraints on magnetic field configurations at later stages. Observations of polarized, millimeter-wavelength continuum emission are ideally suited for determining magnetic field morphology independent of circumstellar disk geometry (Aitken et al. 2002). Polarized thermal emission is generated by elongated dust grains aligned with the magnetic field. Under most conditions, grains are expected to rotate with their long axes perpendicular to the direction of the magnetic field, so that they generate polarized emission perpendicular to the magnetic field direction (see review in Lazarian 2007, as well as Hoang & Lazarian 2009). A set of encouraging observations with the James Clerk Maxwell telescope (JCMT) resulted in tentative detections of polarized 850\,\mu m emission from two T Tauri stars, GM Aur and DG Tau (Tamura et al. 1999). In both cases, the position angle of the polarization vector was consistent with the orientation of the minor axis of the disk, suggesting that the magnetic fields are toroidal. Because the 15\arcsec beam of the JCMT is far larger than the few-arcsecond sizes typical of circumstellar disks, only a single polarization vector could be detected. This result was followed up with theoretical work by Cho & Lazarian (2007), who presented a theoretical justification for the observed globally averaged 2%–3% polarization fraction, and predicted that it should be common to disks around young stars. The Cho & Lazarian (2007) investigation resulted in a theoretical framework that can be used to model the position-dependent fractional polarization of emission from circumstellar disks.

Subsequent observations have not confirmed the expected 2%–3% polarization fraction. Krejny et al. (2009) revisited the DG Tau disk at a wavelength of 350\,\mu m with the Caltech Submillimeter Observatory and did not detect polarized emission in the 9\arcsec beam, placing a 2\sigma upper limit on the integrated fractional polarization of 1.7%. Roughly concurrent interferometric observations of the disks around HD 163296 and TW Hya, selected for their large millimeter fluxes so as to provide the best sensitivity to fractional polarization, also did not detect any polarized emission at a wavelength of 880\,\mu m (Hughes et al. 2009b). Those observations ruled out the fiducial Cho & Lazarian (2007) model at the 10\sigma level, with an estimated integrated upper limit on the polarization fraction of \leq 0.5% (since the interferometric observations spatially resolve the disk, comparisons with integrated polarization fractions from single-dish telescopes are necessarily model-dependent). Hughes et al. (2009b) also explored the theoretical parameter space to determine which factors are most likely to cause the suppression of polarized emission in the observed systems, and determined that some combination of rounding of large grains, reduced efficiency of alignment of large grains with the magnetic field, and/or some degree of magnetic field tangling (perhaps due to turbulence) could plausibly explain the low polarization fraction.

Some ambiguity remains as to whether the Krejny et al. (2009) and Hughes et al. (2009b) results apply to the Tamura et al. (1999) results. In the former case (Krejny et al. 2009), the
wavelength of the DG Tau observation was different enough that the non-detection of polarization could result from wavelength-dependent processes like scattering. In the latter case (Hughes et al. 2009b), both the lack of overlap in targets and the small number of sources introduce uncertainty regarding how broadly applicable the low polarization fraction might be. We have re-observed the two sources that have polarization detections applicable the low polarization fraction might be. We have number of sources introduce uncertainty regarding how broadly dependent processes like scattering. In the latter case (Hughes et al. 2009b), the non-detection of polarization could result from wavelength-wavelength of the DG Tau observation was different enough that the non-detection of polarization could result from wavelength-dependent processes like scattering. In the latter case (Hughes et al. 2009b), both the lack of overlap in targets and the small number of sources introduce uncertainty regarding how broadly applicable the low polarization fraction might be. We have re-observed the two sources that have polarization detections from Tamura et al. (1999), plus another bright HAeBe system, MWC 480. These new observations more than double the sample of circumstellar disks with interferometric, millimeter-wavelength polarization observations, and help to clarify the results of previous observations by revisiting sources with single-dish detections at the same wavelength, but with higher sensitivity and spatial resolution.

Here we present new 880 μm polarimetric observations of the circumstellar disks around GM Aur and MWC 480 with the Submillimeter Array (SMA), and 1.3 mm observations of the disk around DG Tau with the Combined Array for Research in Millimeter Astronomy (CARMA). In Section 3 we compare our observations with the Cho & Lazarian (2007) predictions for the spatially resolved distribution of polarized flux in T Tauri disks, as well as with the overall polarization fraction detected by the JCMT for the GM Aur and DG Tau systems. In Section 4 we discuss the implications of our results for our understanding of magnetic fields in T Tauri stars, and we summarize our work in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. SMA Observations

We conducted 880 μm observations of GM Aur with the SMA polarimeter (Marrone & Rao 2008) on the night of 2009 November 6. Our method was very similar to that described in Hughes et al. (2009b). The array was in the compact-north configuration, with baseline lengths between 16 and 123 m, and the longest baselines along the north–south direction. The weather was good, with 225 GHz opacity of 0.07 and a stable atmospheric phase. MWC 480 was observed on the night of 2009 December 11 in similarly good weather, with stable phase and a 225 GHz opacity of 0.06. The array was in the compact configuration (16–77 m baselines) for the MWC 480 observations.

The data were collected with the receivers tuned to a local oscillator (LO) frequency of 341 GHz (880 μm wavelength). These observations differ from those described in Hughes et al. (2009b) in that a new high-bandwidth observing mode was commissioned on the SMA in the intervening period, which effectively doubled the bandwidth of each sideband from 2 GHz to 4 GHz. We use a uniform correlator configuration that divides each 104 MHz-wide correlator chunk into 128 channels to achieve maximum continuum sensitivity at the highest possible uniform spectral resolution (0.7 km s⁻¹).

For both GM Aur and MWC 480, the quasar 3c111 served as the atmospheric and instrumental gain calibrator, and J0510+180 was included in the observing loop to test the quality of the phase transfer. 3c111, J0510+180, Callisto, 3c273, and 3c279 were used as passband calibrators. Callisto was observed near the beginning of each track to determine the absolute flux scale, and Titan was also included at the end of the MWC 480 track; we derive fluxes of 1.09 and 1.52 Jy for 3c111 on the nights of November 6 and December 11, respectively. The instrumental polarization calibration was carried out as described in Hughes et al. (2009b), by observing 3c273 and 3c279 in the hours before and after transit. We derive consistent instrumental leakage solutions for both sources, and adopt the solutions from the brighter 3c273. The passband, gain, and instrumental polarization calibrations were carried out independently for each 2 GHz segment of each sideband. A summary of the observational parameters is given in Table 1.

| Table 1 |
|---|---|---|---|---|
| **Observational Parameters** | **GM Aur** | **MWC 480** | **DG Tau** |
| **Continuum** | | | |
| LO Frequency (GHz) | 341 | 341 | 224 | 224 | 224 |
| Beam Size (FWHM) | 2″0×1″3 | 2″0×1″3 | 0″9×0″7 | 2″5×2″2 | 1″2×0″9 |
| P.A. | 56° | 12° | 11° | 11° | 11° |
| rms Noise (mJy beam⁻¹) | | | | | |
| Stokes I | 12 | 2.8 | 1.2 | 6.5 |
| Stokes Q and U | 13 | 13 | 2.0 | | |
| Peak Flux Density (mJy beam⁻¹) | | | | | |
| Stokes I | 360 | 220 | 290 | 250 |
| Stokes Q and U (3σ upper limit) | ≤8 | ≤9 | ≤2 | ≤3 | ≤2 |
| Integrated Flux (Stokes I, Jy) | 0.53 | 0.71 | 0.84 | 0.66 |
| CO(3–2) line* | | | | | |
| Beam Size (FWHM) | 2″1×1″3 | 2″5×2″2 | ... | ... | ... |
| P.A. | 75° | 35° | ... | ... | ... |
| rms Noise (Jy beam⁻¹) | | | | | |
| Stokes I | 0.17 | 0.17 | 0.23 | ... | ... |
| Stokes Q and U | 0.28 | 0.28 | ... | ... | ... |
| Peak Flux Density (Jy beam⁻¹) | | | | | |
| Stokes I | 4.6 | 5.4 | ... | ... | ... |
| Stokes Q and U (3σ upper limit) | ≤0.5 | ≤0.7 | ... | ... | ... |
| Integrated Flux (Stokes I, Jy km s⁻¹) | 49 | 9 | 23 | ... | ... |

Note. * Analyses of spectral line data were conducted for SMA only; CARMA has not yet been calibrated for making polarimetric line measurements.
The data were edited and calibrated with the MIR software package\(^4\), and the standard tasks of inversion and beam deconvolution were carried out using the MIRIAD software package.

2.2. CARMA Observations

We conducted $\lambda 1.3$ mm polarimetric observations of DG Tau at CARMA in the C-array (30–350 m baselines) on 2012 March 3, and in the D-array (11–50 m baselines) on 2012 October 13. The data were taken in average weather, with 225 GHz opacities of 0.28 and 0.26, and median atmospheric phases of 90 and 165 $\mu$m for the C and D-array data, respectively. These observations were taken as part of the TADPOL survey, a CARMA key project described in Hull et al. (2012).

The data were collected with the receivers tuned to an LO frequency of 223.821 GHz (1.3 mm wavelength). We use a correlator configuration with three 500 MHz wide bands to measure the dust continuum, and one 31 MHz wide band to map spectral-line emission. In this paper we focus only on the dust continuum polarization from the CARMA data.

The quasars 3c111 and J0510+180 served as the atmospheric and instrumental gain calibrators. 3c84, 3c111, and J0510+180 were used as passband calibrators. Uranus was observed near the beginning of each track to determine the absolute flux scale. Periods of unstable gains during both sets of observations led us to derive slightly lower than expected flux measurements for 3c111 and J0510+180, and thus low values for both the rms noise and the integrated flux of DG Tau. We instead adopt a flux of 317 mJy for DG Tau, based on a greater number of high-quality CARMA observations with overlapping baseline lengths presented in Isella et al. (2009). Using this value, we derive fluxes for J0510+180 of 2.14 Jy on March 3 and 2.18 Jy on October 13; these flux values are consistent with the periods of greatest gain stability, as well as with archival flux measurements from the SMA obtained within weeks of the CARMA observations. The adopted fluxes are consistent with the derived fluxes within the typical 20% systematic flux uncertainty generally expected for CARMA observations at $\lambda 1.3$ mm. The adopted flux values also represent a conservative choice for the flux scale: the lower values derived from periods of unstable gains would not affect the measured fractional polarization, but would artificially decrease the measured rms noise in the maps. Note that the peak Stokes I flux density is lower in C array than D array because the source is slightly resolved.

The leakage corrections are made in a similar manner to the SMA, by observing a strong source (either 3c111 or J0510+180, in these observations) over a range of parallactic angles. Separate leakage solutions are made for the upper and lower sidebands. Since CARMA has a simultaneous, dual-polarization system, an “XYphase” calibration is required to correct for phase differences between the left- and right-circular receivers. This is done by observing artificially polarized noise sources of known position angle.

All data editing and calibration, as well as the standard tasks of inversion and beam deconvolution, were carried out using the MIRIAD software package.

3. RESULTS AND ANALYSIS

We detect no polarized continuum emission from the disks around GM Aur, MWC 480, or DG Tau. In the disks where we were able to perform polarimetric CO(3–2) observations (GM Aur and MWC 480), we do not detect polarized molecular line emission. The measured Stokes $I$ fluxes and Stokes $Q$ and $U$ upper limits for the line and continuum observations are listed in Table 1.

As described in Hughes et al. (2009b), we interpret the polarimetric non-detections with the help of the simulations described in Cho & Lazarian (2007). The Cho & Lazarian (2007) code takes as inputs the stellar properties, viewing geometry, and parametric descriptions of the temperature and density structure of the disk, and then calculates the intensity and fractional polarization of thermal continuum emission as a function of position throughout the disk. It assumes a purely toroidal magnetic field, with dust grains aligned via the radiative torque mechanism (e.g., Dolginov & Mitrofanov 1976; Lazarian 2007). As described in Cho & Lazarian (2007), for disks with intermediate or high inclinations, the code typically predicts a global, integrated polarization fraction of 2%–3%, consistent with the Tamura et al. (1999) observations; however, the polarization fraction varies with position across the disk such that the highest polarization fractions typically occur in the outermost regions of the disk where densities are lowest and grains are most readily aligned. The Cho & Lazarian (2007) code therefore provides a crucial interpretive mechanism that allows us to compare the polarization properties of the high-resolution interferometric observations with the low-resolution, integrated single-dish observations.

We generate initial models of the disk temperature and surface density structure that allow us to reproduce the Stokes $I$ continuum data, based on stellar parameters drawn from the literature and on prior fits to millimeter-wavelength continuum observations by Hughes et al. (2008, 2009a). For DG Tau, no recent power-law fit to high-quality data exists. There is a power-law fit to mid-1990s data from the Plateau de Bure Interferometer (Durty et al. 1996) that has since been superseded by higher sensitivity observations; however, the fitting procedure used for more recent high-quality CARMA data (Isella et al. 2009) cannot be reproduced in the simple parametric form needed for use with the code. Instead, we compromise by constructing a simple power-law fit to the continuum emission in the following way: (1) we assume a disk temperature profile in which the grains are in radiative equilibrium with the central star, which is effectively identical to the temperature profile derived by Dutrey et al. (1996); (2) we adopt an effective outer radius of 89 AU based on the surface density fit of Isella et al. (2009), which exhibits a very sharp drop in surface density at this radius; (3) we assume a surface density power-law index $p = 1$ based on the median value from the Andrews et al. (2009) survey of disk structure in Ophiuchus (the data are only marginally resolved, and therefore of insufficient quality to distinguish between surface density power-law indices); and (4) we then scale the normalization of the surface density to reproduce the observed integrated 1.3 mm flux. The power-law parameters adopted by this method are similar to both the Dutrey et al. (1996) and Isella et al. (2009) solutions. We adopt an inclination for the DG Tau disk of 28.5°, the average result from four data sets in Isella et al. (2010). The stellar and disk parameters used for modeling all three objects are listed with references in Table 2. Stellar parameters (temperature $T$, radius $R$, mass $M$) are indicated with an asterisk in the subscript. $a$ denotes disk radii, inner ($a_{inner}$) and outer ($a_{outer}$). The maximum grain size is $r_{max}$, and the surface density at 100 AU is denoted as $\Sigma_0$. The adopted distance to the system

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\(^4\) See http://cfa-www.harvard.edu/~cqi/mircook.html.
Hughes et al.

4. DISCUSSION

Despite observational and theoretical results implying that a 2%–3% polarization fraction may be common to circumstellar disks (Tamura et al. 1999; Cho & Lazarian 2007), recent interferometric observations of disks around pre-main sequence stars have yielded only non-detections of polarized emission (Hughes et al. 2009b; Krejny et al. 2009). We have revisited both T Tauri stars with previously reported single-dish polarization measurements from the JCMT, as well as a third bright HAeBe system; these observations more than double the sample of circumstellar disks with interferometric measurements of position-dependent magnitude of polarized flux density that should be observed in Stokes $Q$ and $U$ (the models predict no circularly-polarized Stokes $V$ emission). Figures 1, 2, and 3 show a comparison between the data and the polarization models produced by the Cho & Lazarian (2007) code for GM Aur, MWC 480, and DG Tau, respectively. Just as for the HD 163296 and TW Hya systems presented in Hughes et al. (2009b), the theory substantially overpredicts the upper limit on the polarized flux density. While we would expect to detect polarized emission at the $5\sigma$, $7\sigma$, and $8\sigma$ levels for MWC 480, GM Aur, and DG Tau, respectively, we detect no polarized continuum emission from any system.

Table 2

| Parameter | GM Aur | MWC 480 | DG Tau |
|-----------|--------|---------|--------|
| $T_\ast$ (K) | 4000 1 | 8460 2 | 3890 9, 10 |
| $R_\ast$ ($R_{\odot}$) | 1.7 1 | 1.6 2 | 2.87 9, 10 |
| $M_\ast$ ($M_{\odot}$) | 0.84 3 | 1.65 4 | 0.3 9, 10 |
| $p$ | 1.1 5 | 1.0 6 | 1.0 \ldots |
| $a_{\text{inner}}$ (AU) | 20 5 | 0.1$^a$ \ldots | 0.14 11 |
| $a_0$ (AU) | 300 5 | 275 6 | 89 10 |
| $c_{\text{max},i}$ ($\mu$m) | $10^3$ 5 | $10^3$ 6 | $10^3$ \ldots |
| $i$ | 56$^c$ 3 | 37$^c$ 7 | 28.5 12 |
| $d$ (pc) | 140 8 | 140 8 | 140 8 |
| $\Sigma_0$ (g cm$^{-2}$) | 175 \ldots | 275 \ldots | 91 \ldots |

Note. $^a$ Estimated dust destruction radius.

References. (1) Beckwith et al. 1990; (2) Kenyon & Hartmann 1995; (3) Dutrey et al. 1998; (4) Simon et al. 2000; (5) Hughes et al. 2009a; (6) Hughes et al. 2008; (7) Hamidouche et al. 2006; (8) Elias 1978; (9) Muzerolle et al. 1998; (10) Isella et al. 2009; (11) Pinte et al. 2008; (12) Isella et al. 2010.

$d$ is identical for all three sources, since they are all associated with the Taurus star-forming region.

We use these models as inputs to the Cho & Lazarian (2007) code, as described in Hughes et al. (2009b), to predict the
polarization at millimeter wavelengths, and were taken across a wavelength range consistent with the Tamura et al. (1999) results. We report non-detections of polarized millimeter continuum emission from the disks around GM Aur, MWC 480, and DG Tau. These results support the conclusions reached in Hughes et al. (2009b), namely that a low polarization fraction is likely common to the outer regions of bright nearby circumstellar disks. The upper limits for GM Aur, MWC 480, and DG Tau are less significant than those for HD 163296 and TW Hya because Stokes I continuum emission from the new sources is fainter, and thus observations comparatively sensitive in flux are less sensitive in percentage of unpolarized light. Nevertheless, the 2%–3% polarization fractions expected from the work of Cho & Lazarian (2007) and Tamura et al. (1999) are ruled out at the 5σ–8σ level by these observations, strongly suggesting that a substantially lower polarization fraction is common in circumstellar disks.

The observations of GM Aur and DG Tau are particularly interesting in light of the results from Tamura et al. (1999). They report polarization percentages of 3.3% ± 1.3% and 3.0% ± 0.9% for GM Aur and DG Tau, respectively, based on 880 μm observations with the SCUBA polarimeter on the single-dish JCMT. Although the formal significance of these detections is low (2.5σ and 3.3σ, respectively), they note that the alignment of the polarization vector with the disk geometry is particularly suggestive of an association with circumstellar material. Given the stringent upper limits we report here, however, the association with the disk is unlikely. The relatively low inclination of the DG Tau system (28°5; Isella et al. 2010) also makes such a high polarization fraction improbable. Either the JCMT results are spurious, or the emission arises from an extended remnant envelope that is picked up by the 14″ JCMT beam, but is spatially filtered by the SMA and CARMA so as to be undetectable.

In light of the interferometric observations, it is unlikely that significant polarized emission is generated on large (>100 AU) scales by the disk. This result effectively removes the observational justification for expecting an integrated 2%–3% polarization fraction in circumstellar disks. The theoretical justification is also weakened by follow-up work to the Cho & Lazarian (2007) result (Lazarian & Hoang 2007; Hoang & Lazarian 2009), which predicts a smaller alignment efficiency for large grains than is assumed in the original analysis (see Section 4.2.2 of Hughes et al. 2009b). The increased number of sources in the current sample also increases the likelihood that low polarization fractions are common to T Tauri and HAeBe disks. However, it should be noted that all the disks observed so far have been selected for their large millimeter fluxes. They are among the very brightest and most massive circumstellar disks, and therefore may not be a representative sample.

The interpretation presented in Hughes et al. (2009b) still stands, namely that the low polarization fraction is most likely due to a combination of factors including rounding of dust grains, low alignment efficiency of large grains, and/or tangling of magnetic fields on large scales, possibly due to turbulence.
It also bears repeating that a low polarization fraction does not necessarily translate directly to a low magnetic field strength: in the Cho & Lazarian (2007) models, there is effectively a threshold magnetic field strength above which grains will align and below which they will not. The degree of polarization depends far more on grain shape and efficiency of alignment than on the magnetic field strength.

The Hughes et al. (2009a) interpretation has important implications for future observations. While several of the relevant factors (grain rounding and low alignment efficiency) predict that the polarization fraction would be uniformly low in all millimeter-wavelength observations of circumstellar disks, other factors such as magnetic field tangling offer a glimmer of hope for detection. Turbulent motions are expected to occur on maximum size scales that are comparable to the scale height in the disk. All the observations undertaken so far have a spatial resolution of many tens to hundreds of AU, far larger than the scale height at comparable distances from the central star. Even if magnetic fields are ordered at some level, on these large scales any structure could be entirely washed out by integration across such a large beam. Increasing the spatial resolution to probe regions smaller than the scale height of the disk could conceivably resolve ordered structures in the disk, thus allowing detection of polarized emission. In addition, higher resolution observations of the inner disk, where magnetorotational instability (MRI)-induced magnetic field strengths are predicted to be higher, would improve the probability of detection if, in fact, low magnetic field strengths are responsible for the lack of alignment of large grains (see discussion in Bai 2011).

5. SUMMARY

We have revisited the two T Tauri disks previously reported to exhibit significant millimeter-wavelength polarization (GM Aur and DG Tau; Tamura et al. 1999) at higher spatial resolution and sensitivity, and at similar wavelengths. Furthermore, we have added a new polarimetric, millimeter-wavelength observation of the HAeBe disk around MWC 480. We place stringent upper limits on the polarized emission from all three systems, ruling out the fiducial Cho & Lazarian (2007) models at the 5σ–8σ level. These observations support previous observations of other targets (Hughes et al. 2009b), and observations at shorter wavelengths (Krejny et al. 2009), suggesting that the expected 2%–3% polarization fraction is not common in circumstellar disks. Now, with a cumulative sample of three T Tauri and two HAeBe systems, it is clear that the polarization fraction is far lower, even on ∼100 AU scales. Either the previous tentative detections were spurious, or the polarization originated not from the disk but rather from a spatially extended remnant envelope or outflow.

There are many possible explanations for the low polarization fraction, which are laid out in detail in Hughes et al. (2009b). Some of the likely explanations, including rounded grains, inefficient alignment of large grains, or insufficient magnetic field strength for alignment, present a bleak prospect for future observations of polarization in circumstellar disks. However, other possible explanations, including tangling by turbulent motions, suggest that high spatial resolution may permit the detection of ordered structures that are otherwise washed out.
by averaging over larger beam sizes. Sensitive, high-resolution observations, for example with the Atacama Large Millimeter/submillimeter Array, which is now nearing the end of its construction phase, could reveal ordered structure on scales smaller than the disk scale height. Pushing to higher resolution would also allow investigation of magnetic field structure in the inner disk, where MRI-induced magnetic field strengths are predicted to be larger and are therefore more likely to surpass the threshold for grain alignment.

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