**Strong Magnetic Fields Play Important Role in the Filamentary Infrared Dark Cloud G11.11–0.12**

Zhiwei Chen,1,* Ramotholo Sefako,2 Yang Yang,1,3 Zhibo Jiang,1,3 Yang Su,1 Shaobo Zhang1 and Xin Zhou1

1Purple Mountain Observatory, Chinese Academy of Sciences, 10 Yuanhua Road, 210023 Nanjing, China
2South African Astronomical Observatory, PO Box 9, Observatory 7935, Cape Town, South Africa
3School of Astronomy and Space Science, University of Science and Technology of China, 230026 Hefei, China

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**ABSTRACT**

We report on the near-infrared polarimetric observations of G11.11–0.12 with the 1.4 m IRSF telescope. The starlight polarization of the background stars reveals the magnetic fields in the envelope of G11.11–0.12, which are consistent in orientation with the magnetic fields obtained from submillimeter dust polarization. The magnetic fields in G11.11–0.12 are perpendicular to the filament in a large column density range, independent of the relative orientations of G11.11–0.12. The field strength on the plane of the sky in G11.11–0.12 has a typical value of 152 ± 17 μG. The analyses of the magnetic fields and gas velocity dispersion indicate that the envelope of G11.11–0.12 is supersonic and sub-Alfvénic to trans-Alfvénic. The mass-to-flux ratio in the outer part of the envelope is ≤ 1 and slightly increases to ≥ 1 closer to the filament. The weights on the relative importance of magnetic fields, turbulence and gravity indicate that gravity has been dominating the dynamical state of G11.11–0.12, with significant contribution from magnetic fields. The field strength increases slower than the gas density from the envelope to the spine of G11.11–0.12, characterized by the relation $B \propto n^{0.2}$. The observed strength and orientation of magnetic fields in G11.11–0.12 imply that supersonic gas flow is channelled by sub-Alfvénic magnetic fields and is assembled into filaments perpendicular to the magnetic fields. The formation of low-mass stars is enhanced in the filaments with high column density, in agreement with the excess in numbers of low-mass protostars detected in one of the densest part of G11.11–0.12.

**Key words:** ISM: clouds – ISM: magnetic fields – ISM: kinematics and dynamics – ISM: individual objects: G11.11–0.12

1 INTRODUCTION

Filaments are ubiquitous interstellar medium (ISM) structures in galaxies. The formation of filaments is still a controversial topic (see André et al. 2014; Hacar et al. 2022, for reviews). Gas compression due to supersonic turbulence and/or colliding gas flow is supposed to be responsible for the formation of filaments (e.g. Vázquez-Semadeni 1994; Padoan et al. 2001; Vázquez-Semadeni et al. 2006; Heitsch et al. 2006). Once a compressed layer more massive than the average Jeans mass is formed, gravity contraction starts to take control of the evolution, and naturally produce filaments in the cloud and clumps inside the filaments (e.g. Gómez & Vázquez-Semadeni 2014; Naranjo-Romero et al. 2022). The clumps in filaments are potential sites of star formation initialized by gravitational collapse (e.g. Wareing et al. 2019; Yang et al. 2020, 2021). This commonly accepted picture, regarding the formation of filament and subsequent star formation process, makes filaments as the most mysterious ISM structures and the important contributors to real-time star formation (e.g. Ragan et al. 2012; Zhang et al. 2019). In addition to turbulence and gravity, magnetic field has been of long-standing interest in formation and evolution of filaments (e.g. Hanawa et al. 1993; Gehman et al. 1996). Magnetohydrodynamic (MHD) simulations and observations of magnetic fields in filaments in the past decades show that magnetic fields play an important role in shaping filaments and regulating the subsequent star formation inside them (Houde et al. 2004; Goldsmith et al. 2008; Nakamura & Li 2008; Inoue & Inutsuka 2009, 2016; Heitsch et al. 2009; Li et al. 2010; Sugitani et al. 2011, 2019; Chapman et al. 2011; Hennebelle 2013; Soler et al. 2013, 2016; Soler 2019; Matthews et al. 2014; Seifried & Walch 2015; Chen & Ostriker 2015; Chen et al. 2016, 2020; Pillai et al. 2015, 2020; Planck Collaboration et al. 2016b,a; Panopoulou et al. 2016; Malinen et al. 2016; Santos et al. 2016; Hoq et al. 2017; Zamora-Avilés et al. 2018; Mocz & Burkhardt 2018; Fissel et al. 2019; Kusune et al. 2019; Wang et al. 2019, 2020a,b; Su et al. 2020; Körtgen & Soler 2020; Heyer et al. 2020; Girichidis 2021; Lee et al. 2021; Barreto-Mota et al. 2021; Pattie et al. 2021; Eswaraiah et al. 2021; Arzoumanian et al. 2021; Micelotta et al. 2021; Vahdanian & Nejad-Asghar 2022; Li et al. 2022; Stephens et al. 2022; Ibáñez-Mejía et al. 2022; Kwon et al. 2022).

The orientations of magnetic fields with respect to filaments show bimodal distributions, either parallel or perpendicular (e.g. Li et al. 2013; Clark et al. 2014; Li et al. 2014). The bimodal orientations between magnetic fields and filaments reflect the physical link between magnetic field and filaments, otherwise orientations between them should follow a flat distribution. A flip in relative orientation from parallel to perpendicular occurs around column density

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* E-mail: zwchen@pmo.ac.cn
\[ N \sim 10^{21–22} \text{ cm}^{-2} \] (see Hacar et al. 2022; Patte et al. 2022, for reviews). Below this transition column density, filaments or striations are parallel to magnetic fields. Above this transition column density, dense filaments are perpendicular to magnetic fields. Seifried et al. (2020) suggested that the transition column density corresponds to the mass-to-flux ratio \((M/\Phi)\) of a cloud close to the critical value of 1. Magnetically supercritical filaments, or filaments where gravity is stronger than magnetic field, are preferentially perpendicular to magnetic fields. Vice versa, magnetic fields in magnetically subcritical filaments channel the gas flow along the field lines because the cross field motions are resisted by Lorentz force. The bimodal orientations between filaments and magnetic field hold for the subAlfvénic clouds. In the superAlfvénic and supersonic clouds, filaments might be formed via converging flows, and magnetic fields are compressed in filaments; filaments and magnetic fields are parallel and twisted (Barreto-Mota et al. 2021). Strong turbulence could be produced by violent feedback from massive stars (H \(\alpha\) region, stellar winds, supernovae explosion). The swept-up shells by expanding H \(\alpha\) region look like filaments with column density higher than \(\sim 10^{22} \text{ cm}^{-2}\). The magnetic fields within the shells are also compressed by the supersonic shock waves, and are parallel to the filament-like shells (e.g. Krumholz et al. 2007; Arthur et al. 2011; Chen et al. 2017, 2022b). Without massive stars feedback, the turbulence cascaded from large-scale turbulence, magnetic fields, and gravity are merged to determine the evolution of filaments. The magnetic field measurements are rather limited compared to other properties of filaments (e.g. mass, length, velocity dispersion). The poorly known magnetic fields of filaments thus prevent a more comprehensive understanding of the dynamical states of filaments. Given the potential wealth of information stored in the magnetic structure and strength on the evolution of filaments, a more detailed investigation of the magnetic field properties in individual filament is warranted.

Infrared dark clouds (IRDCs) are a type of dense structures mostly appearing as filaments. Due to selection effects, IRDCs are prominent absorption features against the infrared background in the Galactic plane, and are typically located at distances of a few kpc (Carey et al. 1998; Simon et al. 2006; Peretto & Fuller 2009; Rygl et al. 2010). Massive dust condensations and cores, precursors to massive stars and cluster formation, are ubiquitously found within IRDCs (Henning et al. 2010; Ragan et al. 2012). The evolution of IRDCs is expected to be governed by the hybrid of gravity, turbulence, and magnetic fields. The relative importance of these effects has been difficult to determine. While gravity and turbulence can be explored relatively easily from (sub-)millimeter observations, the signatures of magnetic fields are much harder to detect.

The G11.11–0.12 is among the first IRDCs discovered and with the darkest shadows in the Galactic plane (Carey et al. 1998). G11.11–0.12 is at a distance of 3.6 kpc, has a length \(\sim 30 \text{ pc}\), a mass of \(10^5 M_\odot\), and is known to host multiple sites with star formation (Pillai et al. 2006; Henning et al. 2010; Gómez et al. 2011; Shipman et al. 2014; Rosero et al. 2014; Wang et al. 2014; Pillai et al. 2019; Tafoya et al. 2021). The density structure of G11.11–0.12 can be fitted by a central massive cylinder with more extended envelope (Johnstone et al. 2003; Kainulainen et al. 2013). The spine of G11.11–0.12 has a linear mass density \(\sim 600 M_\odot \text{ pc}^{-1}\) that greatly exceeds the critical value of a self-gravitating, non-turbulent cylinder (Kainulainen et al. 2013). The hierarchical segmentation in G11.11–0.12 indicates the dominant role of gravity that has started gravitational collapse (Kainulainen et al. 2013; Wang et al. 2014; Schneider et al. 2015; Ragan et al. 2015; Pillai et al. 2019). The N-PDF analyses of G11.11–0.12 revealed power-law tail in the high column density end, indicative of the gravity-dominated stage (Schneider et al. 2015; Lin et al. 2017). Signatures of gravitational collapse and longitudinal gas flow have been reported in G11.11–0.12 (Tremblin et al. 2014; Beuther et al. 2014; Schneider et al. 2015). It is likely that global collapse in filament scale and fragmenting in clump/core scale are simultaneously occurring in G11.11–0.12. Given the above observational properties, G11.11–0.12 is likely at a relatively late stage of filament formation. Magnetic fields, inherited from the natal ISM that G11.11–0.12 condensed out of, may provide additional information about the formation of G11.11–0.12.

Fiege et al. (2004) proposed that G11.11–0.12 is radially supported by magnetic fields that are predominantly poloidal. Later from submillimeter dust polarization map of G11.11–0.12, magnetic fields in the most massive clump of G11.11–0.12 are perpendicular to the filament (Pillai et al. 2015). Zhang et al. (2014) found that magnetic fields at dense cores scales (\(\lesssim 0.1 \text{ pc}\)) are either aligned within \(40^\circ\) of or perpendicular to the parsec scale magnetic fields (see also Eswaraiah et al. 2021). In this paper we present the large-scale magnetic fields of G11.11–0.12, derived from near-IR starlight polarization of background stars. The study of the large-scale magnetic fields is essential to explore the effects of magnetic field in the formation and evolution of G11.11–0.12.

2 DATA ACQUISITION

2.1 IRSF/SIRPOL Observations

The data were taken with SIRPOL on the 1.4 m InfraRed Survey Facility (IRSF) telescope at the South African Astronomical Observatory, Sutherland, South Africa. SIRPOL is a single-beam polarimeter with an achromatic half-wave plate rotator unit and a polarizer attached to the near-IR camera SIRIUS (Nagayama et al. 2003; Kandori et al. 2006). SIRPOL enables wide-field (\(\sim 8^\prime \times 8^\prime\)) and simultaneous polarization imaging observation at a pixel scale \(0^\prime.45\) in the \(\text{JHK}_s\) bands. The observations were made during the night of 2018 July 21. To cover the entire extent of G11.11–0.12, we designed a grid of three positions on the sky. In each grid position, three sets of observations were conducted. Each set took 30 s exposures time at 4 wave-plate angles (in the sequence of \(0^\circ, 45^\circ, 22.5^\circ,\) and \(67.5^\circ\)) at 10 dithered positions. The total integration time was 1200 s per wave-plate angle in one grid position. Including observation overheads, the total observation time in one grid position was 83 min. The total time spent on the entire extent of G11.11–0.12 was 4.1 hr. The airmass during the observations was in the range of 1.03 – 1.60. Observations with lower airmass generally have smaller full width half maximum (FWHM) value. The measured FWHM averaged for the point sources in the three grid positions have a range from less than 3 pixels to around 4 pixels, or \(\sim 1^\prime.5–4^\prime.8\).

The data reduction and aperture photometry for the \(\text{JHK}_s\) polarimetric images are referred to in Chen et al. (2022b). Following the procedure of polarization calculation in Chen et al. (2022b), we obtained the \(\text{JHK}_s\) starlight polarization of sources along the line of sight (LOS) toward G11.11–0.12. The polarization position angle (P.A.) \(\theta_{PA}\) is counted counterclockwise from the north to the east in the equatorial coordinate. Sources satisfying \(P \geq 2 \delta P\) are utilized in this work. The uncertainty of \(\theta_{PA}\) is obtained from \(\delta\theta_{PA} = 28^\circ.6 \delta P/P\), thus we have \(\delta\theta_{PA} \leq 14^\circ\) for the sources with \(\text{JHK}_s\) starlight polarization in the field of G11.11–0.12.
2.2 VVX photometry

We employed the near-IR photometry of the VVVX survey, an extension of the Vista Variables in the Via Lactea (hereafter VVV) survey (Minniti et al. 2010). G11.11–0.12 was covered by tile e0954, as part of the VVVX Data Release 1. The $JHK_s$ images and catalogs of the e0954 tile were retrieved from the European Southern Observatory (ESO) Science Archive Facility 1. The VVVX $JHK_s$ catalogs include magnitudes from a series of aperture diameters ranging from 1$''$ to 24$''$ (aperture 1 to aperture 13). We use the aperture 3 magnitudes with aperture diameter of 2$''$. The calibrated $JHK_s$ magnitudes can be derived from the aperture 3 fluxes and the zero point calibration $MAGZPT$ in the VVVX catalogs using the equation:

$$CalMag = MAGZPT - 2.5 \log Flux - APCORN,$$

where $APCORN$ corresponds to the aperture correction term of aperture 3 that is also integrated in the VVVX catalogs 2.

2.3 CO Molecular Data of G11.11–0.12

The velocity range of the bulk emission of G11.11–0.12 is from 26 to 35 km s$^{-1}$, obtained from CO J=3-2 line emission (Schneider et al. 2015). The optically thinner lines such as $^{13}$CO and C$^{18}$O J=1-0 were not presented in Schneider et al. (2015). In this work we employed the CO and CO isotopes $J = 1 − 0$ data of G11.11–0.12 from the Milky Way Imaging Scroll Project (MWISP) project, an unbiased Galactic plane CO survey in the northern sky (see more details in Su et al. 2019). After fitting the baseline and calibrating the main beam efficiency, the reduced position-velocity intensity (PV) cubes with a grid spacing of 30$''$ have a typical root mean square noise level of ~ 0.5 K for $^{12}$CO J=1-0 emission and ~ 0.3 K for $^{13}$CO/C$^{18}$O J=1-0 emission at a channel width of 61 kHz ($\sim 0.16 − 0.17 $ km s$^{-1}$). The spatial resolutions of the CO PV cubes are close to 50$''$.

Adopting the same velocity range as Schneider et al. (2015), we derive the moment 0 (integrated intensity) and moment 2 (line width) maps of the CO, $^{13}$CO and C$^{18}$O J=1-0 emissions from the MWISP CO PPV cubes. For the molecular hydrogen column density $N(H_2)$ map of G11.11–0.12, we follow the steps used in Chen et al. (2022b), including excitation temperature estimate of molecular gas from CO J=1-0 emission, calculating column densities of $^{13}$CO and C$^{18}$O molecules ($N(^{13}$CO), $N(C^{18}$O)), optical depth correction for $N(^{13}$CO) and conversion from $N(^{13}$CO)/$N(C^{18}$O) to $N(H_2)$. The $N(H_2)$ map of G11.11–0.12, given a LOS extent of the filament, yields an estimate of molecular gas number density $n(H_2)$. The moment 2 map of $^{13}$CO J=1-0 emission evaluation the velocity dispersion distribution of G11.11–0.12. The density, velocity dispersion of molecular gas derived from CO molecular line data and magnetic fields traced by starlight polarization are the fundamental parameters characterizing the dynamical state of G11.11–0.12.

3 RESULTS

Figure 1 shows the three-color composite image of G11.11–0.12. The combined IRSF observations cover the entire G11.11–0.12 filament (seen as the dark cloud in Figure 1) and sufficient areas surrounding the filament. Checking the CO gas emission, the near-IR polarization observations span over the dense filament and surrounding fields of lower gas emission.

The near-IR polarization observations by the IRSF telescope are able to trace magnetic fields in the surrounding fields of lower density. Nevertheless, the dense filament has $N_{\text{dust}}$ well above $4 \times 10^{22}$ cm$^{-2}$ (Fig.2.A.2 in Schneider et al. 2015), which is beyond the detection limit of starlight polarization, even in the near-IR wavelength for a 1.4 m class telescope. Near-IR polarization observations by a larger telescope might have sufficient sensitivity in detecting the faint starlight of stars lying behind IRDCs.

The $N_{\text{dust}}$ map of G11.11–0.12 constructed from the multiwavelength maps made with Herschel clearly shows that the spine of G11.11–0.12 is surrounded by gas of lower density Schneider et al. (2015). Only the spine of G11.11–0.12 appears pronounced in the submillimeter wavelength observed with the Jim Clerk Maxwell Telescope (JCMT) (Carey et al. 2000). Pillai et al. (2015) first obtained the magnetic fields toward the densest part of G11.11–0.12 from the archival calibrated 850 µm polarization data taken with the polarimeter SCUPOL on JCMT (Greaves et al. 2003), and these generally trace the spine of G11.11–0.12 that is dense and compact, and is bright in submillimeter (see Figure 1 in Pillai et al. (2015)). The submillimeter polarization data from Planck mission are sensitive to the more extended structures. Nevertheless, the spatial resolution of Planck submillimeter polarization data is worse than 5', resolution at which G11.11–0.12 is not well resolved. The Planck polarization data are the integrated contributions from dust emission along the same LOS to G11.11–0.12, including substantial contribution from the Sagittarius spiral arm of the Milky Way. Starlight polarization, especially in the near-IR wavelengths, has the potential to reveal magnetic fields in the diffuse parts of G11.11–0.12. The polarization degrees measured in multiple wavelengths were found to follow a power law $P_{\lambda 1} / P_{\lambda 2} \propto (\lambda_1 / \lambda_2)^{-\alpha}$ (Whittet et al. 1992; Chen et al. 2012), confirming the interstellar origin for starlight polarization. When the background starlight polarization is carefully classified, the starlight polarization due to dust extinction in G11.11–0.12 carries the information of dust alignment. Although the mechanisms responsible for dust alignment with respect to magnetic fields remain an open question, the elongated dust grains with short axes aligned with magnetic fields are the widely used probes for the on-the-sky components of magnetic fields (Andersson et al. 2015). The starlight polarization caused by dust extinction is parallel to the on-the-sky component of magnetic fields (hereafter $B_{\text{sky}}$).

3.1 Classifying Reddened Background Stars

The detection limit of the 1.4 m IRSF telescope is likely not deep enough to detect sufficient background stars. Similar to the approach used in Chen et al. (2017, 2022b), we combine the $JHK_s$ starlight polarization ($P_{\lambda 1} \geq 2 \sigma P_{\lambda 1}$) with the VVVX photometry. Applying a maximum separation of 1$''$ in crossmatch, we derive $JHK_s$ starlight polarization coincident with the deeper VVVX $JHK_s$ photometry. There are 637 sources in the J band, 749 sources in the H band, and 624 sources in the K$_s$ band, that have starlight polarization $P_{\lambda 1} \geq 2 \sigma P_{\lambda 1}$ and deeper $JHK_s$ photometry.

With the deep VVVX near-IR photometry, we apply the classical $J − H$ versus $H − K_s$ color-color diagram to classify background stars that mostly show large $J − H$ and $H − K_s$ colors. Figure 2 shows the color-color diagram for the starlight polarization with the VVVX $JHK_s$ photometry in the $JHK_s$ bands. Two populations exist in the color-color diagrams. Stars with low $H − K_s$ and $J − H$ colors and others with higher colors and reddened along the extinction line. Similar to the criteria in Chen et al. (2022b) for separating background.

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1 The VVVX datasets are available at https://doi.eso.org/10.18727/archive/68
2 See https://www.eso.org/mi/apl/v1/public/releaseDescriptions/187

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Figure 1. A three-color composite image of G11.11–0.12, made from the VVVX $J$ (blue), $H$ (green), and $K_s$ (red) images. The coverage of the IRSF observations is marked by the inserted grid shape made from three different pointings of IRSF, within the white lines and as discussed in Section 2.1.

Figure 2. $J - H$ vs. $H - K_s$ color-color diagrams of the sources in the $JHK_s$ bands from left to right respectively. The main-sequence intrinsic colors (highlighted in green) are adopted from Pecaut & Mamajek (2013). The background and foreground stars are lying within the areas enclosed by the red and blue dashed lines respectively. A reddening vector of length $A_v = 15$ mag is displayed as the arrow in the $JHK_s$ bands respectively.

and foreground stars, the criteria for background stars (vice versa for foreground stars) of G11.11–0.12 are

$$J - H \leq 2.1 \times (H - K_s) + 0.65$$

$$J - H \geq 2.1 \times (H - K_s) - 0.65$$

and are displayed as the red dashed lines in Figure 2. The numbers of background stars are 97, 334, and 364 in the $J$, $H$ and $K_s$ bands, respectively. In contrast, the numbers of foreground stars are 341, 232, 86 in the $JHK_s$ bands, respectively. In the short wavelength, starlight polarization is dominated by foreground stars. The fraction of background stars increases toward longer wavelengths.

The extinction along the LOS of G11.11–0.12 is much higher than that pointing to higher galactic latitudes. The Gaia mission provides accurate stellar parallaxes up to several kilo parsecs (Gaia Collaboration et al. 2016, 2021), depending on the level of interstellar extinction along the LOS. From the star distance catalog (Bailer-Jones et al. 2021), we retrieve distance estimates of $JHK_s$ starlight polarization by using a match radius of $1''$. We consider the sources with narrow range of distance estimates, defined by
3.2 Foreground Polarization

The interstellar polarization arises from dust foreground to G11.11–0.12 can not be neglected. Those contributions should be removed from the starlight polarization of background stars prior to the analyses of magnetic fields. This correction of foreground polarization has been widely applied when the foreground polarization is significant and ordered (e.g. Clemens et al. 2013; Eswaraiah et al. 2019; Devaraj et al. 2021). In some cases the foreground polarization is small and random, the foreground polarization can be neglected (e.g. Chen et al. 2017).

Toward the filament of G11.11–0.12, foreground polarization in the $K_s$ band is computed from the starlight polarization of 86 foreground stars in the same band. The spatial distributions of foreground polarization are split into grid with a spacing of $5^\prime$. The weighted mean Stokes value of the foreground contribution in a grid is computed from the foreground polarization within the same grid. Every background star is assigned to a nearest grid with foreground polarization. The corrected Stokes values of background stars are obtained as $Q_{corr} = Q_{bg} - Q_{tg}$ and $U_{corr} = U_{bg} - U_{tg}$. The corrected polarization degree ($P_K$) and $\theta_{PA}$ are calculated using Equations (6) and (7) in Chen et al. (2022b). The foreground-corrected starlight polarization of 364 stars in the $K_s$ band are capable of tracing the local $B_{sky}$ in G11.11–0.12. Table 1 lists the IRSF polarimetric and VVVX photometric properties of the 364 stars with foreground-corrected polarization in the $K_s$ band.

### Table 1. Starlight Polarization in the $K_s$ band of the 364 foreground-corrected Background Stars in the G11.11–0.12 Filament.

| ID   | R.A. (deg) | Decl. (deg) | $P_K$ (%) | $\delta P_K$ (%) | $\theta_{PA}$ (°) | $\delta \theta_{PA}$ (°) | $J$ (mag) | $Jerr$ (mag) | $H$ (mag) | $Herr$ (mag) | $K$ (mag) | $Kerr$ (mag) |
|------|------------|-------------|------------|------------------|-------------------|-------------------------|-----------|--------------|-----------|--------------|-----------|--------------|
| 1    | 272.519271 | -19.521586  | 2.1        | 0.1              | 27.0              | 1.0                     | 14.900    | 0.004        | 12.004    | 0.001        | 10.395    | 0.001        |
| 2    | 272.482277 | -19.518889  | 1.7        | 0.1              | 85.4              | 1.9                     | 14.393    | 0.003        | 12.118    | 0.001        | 10.927    | 0.002        |
| 3    | 272.545577 | -19.517027  | 4.3        | 0.1              | 43.8              | 0.8                     | 17.315    | 0.029        | 13.329    | 0.003        | 11.383    | 0.002        |
| 4    | 272.461334 | -19.516866  | 4.4        | 0.4              | 19.3              | 2.8                     | 18.563    | 0.088        | 14.320    | 0.008        | 12.303    | 0.005        |
| 5    | 272.503073 | -19.519302  | 1.9        | 0.8              | 60.0              | 10.3                    | 16.187    | 0.011        | 13.773    | 0.005        | 12.599    | 0.006        |
| 6    | 272.552427 | -19.514424  | 3.3        | 0.2              | 32.9              | 1.9                     | 17.374    | 0.030        | 13.673    | 0.004        | 11.878    | 0.003        |
| 7    | 272.478238 | -19.513628  | 1.0        | 0.2              | 61.2              | 4.1                     | 15.065    | 0.005        | 12.595    | 0.002        | 11.448    | 0.002        |
| 8    | 272.490461 | -19.510993  | 1.1        | 0.4              | 113.6             | 12.2                    | 16.133    | 0.011        | 13.597    | 0.004        | 12.390    | 0.005        |
| 9    | 272.571790 | -19.509837  | 3.5        | 0.1              | 18.8              | 0.5                     | 15.717    | 0.008        | 12.062    | 0.001        | 10.338    | 0.001        |
| 10   | 272.524216 | -19.507947  | 2.6        | 0.2              | 41.7              | 1.9                     | 14.667    | 0.004        | 12.544    | 0.002        | 11.548    | 0.002        |

Only one portion of this table is shown here. The full version is available online (Chen et al. 2022a).

(3.3 The Local $B_{sky}$ in G11.11–0.12)

Figure 3 shows the distributions of starlight polarization segments overlaid on the N(H$_2$) map derived from C$^{18}$O emission. In Figure 3, the rotated $\theta_{PA}$ is measured counterclockwise relative to the north Galactic pole. Unlike the $B_{sky}$ parallel to the Galactic plane in other clouds (e.g. Chen et al. 2017, 2022b), the local $B_{sky}$ traced by the ordered starlight polarization segments are not always parallel to the Galactic plane.

Roughly according to the orientations of G11.11–0.12, we split G11.11–012 into four parts.

**Part A:** This part is in the range $11^\circ.24 < l < 11^\circ.34$. Part A is oriented roughly parallel to the Galactic plane and has the lowest $N_{dust}$ values of $2 - 3 \times 10^{22}$ cm$^{-2}$.

**Part B:** This part is in the range $11^\circ.15 < l < 11^\circ.24$. Different from part A, part B has an inclination angle of 50° from the Galactic plane. The $N_{dust}$ of part B is higher than that of part A.

**Part C:** This part is in the range $11^\circ.04 < l < 11^\circ.15$. Part C contains the massive dust condensation P1 (Johnstone et al. 2003), and the magnetic fields in this part were studied with dust polarization (Pillai et al. 2015). Part C is one of the two densest parts in G11.11–0.12 and is inclined at 30° to the Galactic plane.

**Part D:** This part is in the range $10^\circ.93 < l < 11^\circ.04$. Part D contains the massive dust condensation P6 (Johnstone et al. 2003; Wang et al. 2014) and the ‘starless core’ (Pillai et al. 2019). Part D is one of the two densest parts in G11.11–0.12. Part D is inclined at 40° to the Galactic plane.

Due to the lowest hydrogen column density, the number of starlight polarization is largest toward part A. Starlight polarization in this part is well aligned. The $B_{sky}$ is perpendicular to this part of G11.11–0.12.

Continuously connected with part A, part B changes its orientation relative to the Galactic plane. In the area close to part A, starlight polarization is consistent with that of part A. Toward the dense area of part B, a few segments are perpendicular to the filament. However, these starlight polarization have low degrees and are chaotic in $\theta_{PA}$.

The $N_{dust}$ in the spine of part C reaches to $\geq 5 \times 10^{22}$ cm$^{-2}$. Only one star is located at the spine of part C and shows distinct $\theta_{PA}$ compared with other stars in part C. This star is likely a fore-
**Figure 3.** Molecular hydrogen column density derived from $^{12}$CO emission in the velocity range 26–35 km s$^{-1}$, overlaid with the red contours of $N_{\text{dust}}$ from $2 \times 10^{22}$ cm$^{-2}$ to $8 \times 10^{22}$ cm$^{-2}$ in steps of $10^{22}$ cm$^{-2}$ (Schneider et al. 2015). The foreground-corrected $K_s$-band starlight polarization is displayed as the green segments with lengths in proportion to polarization degree. The white box outlines the region for which dust polarization was analyzed (Pillai et al. 2015). The mean P.A. of dust polarization is displayed as the white segment.

**Figure 4.** Polarization angle dispersion map with grid spacing of $2' \times 2'$, overlaid with the red contours of $N_{\text{dust}}$ from $2 \times 10^{22}$ cm$^{-2}$ to $8 \times 10^{22}$ cm$^{-2}$ in steps of $10^{22}$ cm$^{-2}$ (Schneider et al. 2015). The average polarization is displayed as the green segment on each grid, with length in proportion to the average polarization degree. The white box and segment are the same as in Figure 3.
ground contamination with red intrinsic color. Starlight polarization only catches the $B_{\text{sky}}$ in the surrounding envelope of part C. The $B_{\text{sky}}$ traced by starlight polarization in the envelope is consistent with the magnetic fields obtained from dust polarization, which are represented by the white segment in the densest dust condensation of part C (Pillai et al. 2015). The starlight polarization traces the envelope of G11.11–0.12, while dust polarization traces the spine of G11.11–0.12. The consistency of $B_{\text{sky}}$ in envelope of parsec scale and dense core of sub-parsec scale indicates that magnetic fields are perpendicular to part C of G11.11–0.12.

Part D is as dense as part C. Dust condensations in part D have been studied (Wang et al. 2014; Pillai et al. 2019). Few starlight polarization is detected in the spine of part D. In the envelope, $B_{\text{sky}}$ traced by starlight polarization is roughly perpendicular to part D.

Figure 4 presents the mean weighted starlight polarization in grid box of $2' \times 2'$, overlaid on the map of polarization angle dispersion. The weighted mean starlight polarization demonstrates that the spine of G11.11–0.12 is perpendicular to $B_{\text{sky}}$, independent of the orientations relative to the Galactic plane.

### 3.4 Strength of $B_{\text{sky}}$

Due to the limitation of starlight polarization, $B_{\text{sky}}$ traced by this method is limited to gas of low to moderate density. Therefore, the field strength is more representative of the envelope rather than the spine of G11.11–0.12. Pillai et al. (2015) estimated a total strength of $> 267 \pm 26 \mu G$ for the dense condensation in part C (white rectangle in Figure 3). In the envelope of G11.11–0.12, the gas density is much lower than that in the spine.

Assuming energy equipartition between turbulence and perturbed magnetic fields is

$$\frac{1}{2} \rho \delta v^2 \sim \frac{\delta B^2}{8\pi},$$

the polarization angle dispersion $\delta \phi = \frac{\delta B}{B_0}$ yields the Davis-Chandrasekhar-Fermi (DCF) method (Davis & Greenstein 1951; Chandrasekhar & Fermi 1953)

$$B_{\text{sky}} \approx Q \sqrt{3\pi \rho \frac{\delta v}{\delta \phi}},$$

(4)

where $Q$ is the correction factor, $\rho$ is the gas density, $\delta v$ is the gas velocity dispersion and $\delta \phi$ is polarization angle dispersion.

The $^{13}$CO emission is optically thin within the envelope of G11.11–0.12. The moment 2 map of $^{13}$CO emission provides the velocity dispersion $\delta v$ of molecular gas across G11.11–0.12. The median $\delta v$ values of the areas overlapping with starlight polarization are extracted from the moment 2 map of $^{13}$CO emission. The density of molecular gas, or molecular hydrogen number density $n(H_2)$ multiplied by $2.83 m_1 g/(m_1 H)$ is the mass of a single hydrogen atom), is always the most challenging part in characterizing the fundamental properties of molecular cloud. Kainulainen et al. (2013) estimated a mean large-scale $n(H_2) \approx 0.5 \times 10^3\mathrm{cm}^{-3}$ of G11.11–0.12. Assuming the LOS extent $l = 10 \mathrm{pc}$ for the envelope of G11.11–0.12, $n(H_2)$ is approximately $N(H_2)/l$. The median $n(H_2)$ of part A is $0.7 \times 10^3\mathrm{cm}^{-3}$, roughly consistent with the large-scale value of $n(H_2) \approx 0.5 \times 10^3\mathrm{cm}^{-3}$ in Kainulainen et al. (2013).

The $B_{\text{sky}}$ of G11.11–0.12 shows a certain degree of large-scale structure. Independent of the orientations of the four parts of G11.11–0.12, the $B_{\text{sky}}$ is perpendicular to the four parts. Therefore, the $\delta \phi$ due to turbulence of molecular clouds can be obtained from the angular dispersion function (Falceta-Gonçalves et al. 2008; Hildebrand et al. 2009). The angular dispersion function (ADF) method obtains a measure of the difference in polarization angle of $N(l)$ pairs of polarization separated by displacement $l$:

$$\langle \Delta \Phi^2(l) \rangle^{1/2} = \left[ \frac{1}{N(l)} \sum_{i=1}^{N(l)} (\Phi(x) - \Phi(x+l))^2 \right]^{1/2}$$

The polarization angle dispersion attributed to the turbulent magnetic field $B_l(x)$ and the large-scale structured $B_0(x)$ are folded into $\langle \Delta \Phi^2(l) \rangle^{1/2}$. If the large-scale and turbulent magnetic fields are statistically independent and turbulent dispersion of polarization angle is a constant $b$ for $l$ larger than the correlation length $\delta$ characterizing $B_l(x)$, the following equation holds

$$\langle \Delta \Phi^2(l) \rangle^{1/2} = b^2 + m^2 l^2 + \sigma_M^2(l),$$

(5)

where $\delta < l < d$, where $d$ is the typical length scale of variations in $B_0(x)$, and $\sigma_M(l)$ is the measurement uncertainty. Figure 5 shows the ADF of the four parts along with the best fit from Equation 5 using the first five data points ($l < 2'5$) to ensure $l < d$ as much as possible. The constant $b$ is determined by the zero intercept of the best fit to the ADF at $l = 0$. The ratio of the turbulent to large-scale magnetic field is a function of constant $b$

$$\frac{\langle B^2 \rangle^{1/2}}{B_0} = \frac{b}{2 - b^2}.$$
Table 2. The physical properties within the four parts of G11.11–0.12. Part C is split into two halves, Lower C and Higher C, separated by the spine of part C. Field strengths in both halves are estimated.

| Part  | $n(H_2)$ $(10^4$ cm$^{-3}$) | $\delta v$ (km s$^{-1}$) | $\delta \phi$ (°) | $B_{sky}$ ($\mu$G) | $v_A$ (km s$^{-1}$) | $M_A$ |
|-------|---------------------------|------------------------|--------------|----------------|----------------|-----|
| A     | 0.7                       | 1.7                    | 7 ± 1        | 156 ± 19       | 7.5           | 0.3 |
| B     | 1.0                       | 1.9                    | 18 ± 3       | 68 ± 23        | 2.8           | 0.6 |
| Lower C | 1.5                       | 1.9                    | 11 ± 4       | 149 ± 29       | 4.9           | 0.4 |
| Higher C | 1.2                       | 2.1                    | 23 ± 3       | 67 ± 29        | 2.5           | 0.8 |
| D     | 1.4                       | 2.1                    | 29 ± 9       | 53 ± 30        | 1.8           | 1.1 |

Figure 5. The angular dispersion function (ADF) vs. displacement distance for the four parts of G11.11–0.12. The solid line represents the fit to the ADF of the four parts. The measurement uncertainties were subtracted prior to computing the fits to the data.

(Falceta-Gonçalves et al. 2008). We assume that the field strength of part A is appropriate for the entire envelope of G11.11–0.12, and the larger polarization angle dispersion of parts B, C, and D are due to the projection effect of field lines. The highly ordered starlight polarization toward part A and lower half of part C imply that the projection effect due to the field orientation is small for the two parts. We adopt a total field strength $|B| \approx (B_{sky}) \approx 152 \pm 17 \mu$G as the typical value for the magnetic fields in the envelope of G11.11–0.12.

4 DISCUSSION

The starlight polarization within the $2' \times 2'$ grid spacing across G11.11–0.12, in principle, provides the information of $M_A$ and $(M/\Phi)$ distribution across G11.11–0.12, coordinated with the maps of $N(H_2)$ and $\delta \phi$. In each $2' \times 2'$ grid, the polarization angle dispersion is the statistical dispersion of $\theta_{PA}$ of the starlight polarization within a grid. Figure 4 presents the distribution of $\theta_{PA}$ dispersion with a grid spacing of $2' \times 2'$. The $M_A$ map based on the $\theta_{PA}$ dispersion map is presented in Figure 6. The envelope of G11.11–0.12 is sub-Alfénic, indicating that magnetic field channels the gas flow from the envelope to the spine of G11.11–0.12.

The $(M/\Phi)$ weights the importance of magnetic fields relative to gravity. A $M/\Phi$ relative to a critical ratio given by $(M/\Phi)_{crit} = \frac{1}{2\pi\sqrt{G}}$ (Nakano & Nakamura 1978) is characterized by a dimensionless value

$$\lambda = \frac{M/\Phi}{(M/\Phi)_{crit}} = 2\pi\sqrt{G} \mu m_H \frac{N(H_2)}{B_{sky}},$$

where $G$ is the gravitational constant, $\mu = 2.83$ is the average molecular weight of molecular gas (Kauffmann et al. 2008). The field strength and $N(H_2)$ maps yield the distribution of $\lambda$ across G11.11–0.12, as shown in the bottom panel of Figure 6. It is not surprising that the spine of G11.11–0.12 has the highest $\lambda$ values, because the field strength within the spine of G11.11–0.12 is severely underestimated. If adopting the field strength of $\sim 300 \mu$G, the value of $\lambda$ toward the dense clump of part C filament is reduced to a level of marginally supercritical (Pillai et al. 2015). However, the field strength within the envelope is reliable, because of the sub-Alfénic turbulence and polarization angle dispersion $< 25^\circ$. The $\lambda$ within the envelope is magnetically subcritical or marginally supercritical, indicating that magnetic field plays important role in the envelope of G11.11–0.12.

Due to the limitation of near-IR starlight polarization, the magnetic fields within the envelope of G11.11–0.12 are much more constrained than in the spine of G11.11–0.12. Previous study of the magnetic field toward the spine of G11.11–0.12 (part C filament) suggested important role of magnetic fields with respect to turbulence and gravity (Pillai et al. 2015). Recent observations focusing on the star formation of G11.11–0.12 demonstrate that star formation is on-going within the densest parts (part C and part D) of G11.11–0.12 (Spina et al. 2014; Wang et al. 2014; Pillai et al. 2019). Our work obtains, for the first time, the magnetic fields in the envelope of G11.11–0.12, which are essential to the understanding of the formation of G11.11–0.12.

The magnetic fields orientation in the envelope of G11.11–0.12 in this work are almost identical to that in the spine of part C (Pillai et al. 2015). This consistency between parsec scale and sub-parsec scale magnetic field orientations suggests the important role of magnetic fields in the mass assembling of G11.11–0.12. The typical field strength in the envelope of G11.11–0.12 is $152 \pm 17 \mu$G. The median $n(H_2)$ of part A is $0.7 \times 10^3$ cm$^{-3}$. Pillai et al. (2015) estimated magnetic field strength of $> 267 \pm 26 \mu$G in the spine of part C. They adopted $n(H_2) \approx 3 \times 10^4$ cm$^{-3}$ in the estimate of magnetic field strength. The density contrast between the spine and the envelope of G11.11–0.12 is $\sim 43$. If adopting the relation $|B| \propto \rho^{0.65}$ discussed in Crutcher (2012), the magnetic field strength contrast between the spine and the envelope is as high as $\sim 10$, much higher than the observed contrast $\sim 2$. The observed magnetic field contrast
Magnetic Fields of G11.11–0.12

between the spine and the envelope of G11.11–0.12 does not follow the nominal scaling relation between magnetic field strength and density. Magnetic fields are not significantly enhanced in the spine of G11.11–0.12 as material is assembled onto the spine. This can be explained by gas flow guided by the field lines. Gas flow along the field lines is inefficient to compress magnetic fields, leading to little enhancement of field strength when gas flows are merging onto the filament. The flat scaling relation $|B| \propto n^{0.2}$ found for G11.11–0.12 is important for the evolution of G11.11–0.12. First, dense spine can be easily formed without much magnetic field resistance. Second, the spine becomes magnetically supercritical because the field strength is increasing slower than density in the spine. The spine could reach a high volume density, resulting in a small thermal Jeans mass that is conducive to forming low-mass stars (Li et al. 2010). The outflows traced by high-velocity CO $2 \rightarrow 1$ emission toward the ‘starless core’ in part D of G11.11–0.12 are mostly driven by low-mass protostars with masses below the sensitivity of $\sim 1 – 2 M_\odot$ (Pillai et al. 2019). This overabundance of low-mass protostars in the densest part D of G11.11–0.12 and the perpendicular magnetic fields as shown in this work are in agreement with the predictions drawn from the MHD simulations (Li et al. 2010).

The $N$(H$_2$) of part A is in the range $0.3 – 2 \times 10^{22}$ cm$^{-2}$, a value consistent with the transition column density $\sim 10^{21–21.5}$ cm$^{-2}$ obtained from MHD simulations (Seifried et al. 2020). Moreover, the $\lambda$ is overall smaller than 1 in the outer areas of part A, and increases to larger than 1 closer to the filament. Because the coverage of IRSF

Figure 6. Alfvenic Mach number map (top panel) and dimensionless ($M/\Phi$) map (bottom panel) toward G11.11–0.12. The average polarization is the same as in Figure 4, and it is displayed as the black segments. The white contours are the same as the red contours in Figure 3.
observations is not large enough to cover the most extended part of G11.11–0.12. Magnetic fields in the most diffuse areas of part A are assumed to be perpendicular to the G11.11–0.12 filament. Our work does not observe the flip from parallel to perpendicular orientation, but only obtains the magnetic fields in the envelope of G11.11–0.12 in which gravity has already been important. The largest distance from the edge to the spine of G11.11–0.12 is about 4 pc. The magnetic fields are perpendicular to the G11.11–0.12 filament in scale smaller than 4 pc.

G11.11–0.12 is a filamentary IRDC and it is among the densest types of filaments. The CO molecular line observations present supersonic turbulence $v_\delta \sim 2$ km s$^{-1}$. Coordinated with the measurements of magnetic fields in this work, the supersonic turbulence is found to be sub-Alfvénic ($M_A < 0.5$) in the envelope of G11.11–0.12. The dynamically important magnetic fields in the envelope of G11.11–0.12 have general applications in the formation of dense filaments. The supersonic and sub-Alfvénic turbulence can easily compress gas along the field lines, resulting in density enhanced filament perpendicular to the field lines (Nakamura & Li 2008; Li et al. 2010). As soon as the density enhanced filament has a mass greater than the average Jeans mass (this condition is easily reached in supersonic turbulence), global collapse starts to take its role (Gómez & Vázquez-Semadeni 2014). Gas in the envelope free-falls into the spine of the filament of the lowest gravitational potential. In the case of strong magnetic fields, gas flow along the field lines is faster than in the direction perpendicular to field lines. Global collapse is more efficient along the magnetic fields, resulting in density structures perpendicular to the strong magnetic fields. Barreto-Mota et al. (2021) found that gravity helps the creation of density structures perpendicular to magnetic fields in their sub-Alfvénic models. We suggest that dense filament like G11.11–0.12 is more easily formed in sub-Alfvénic self-gravitating turbulent molecular clouds. Magnetic fields determine the orientation of the filaments formed in such clouds.

DATA AVAILABILITY

The full version of Table 1 is available in https://www.scidb.cn/en, at https://dx.doi.org/10.57760/sciencedb.01942 (Chen et al. 2022a).

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