Revealing Gravitational Collapse in the Serpens G3–G6 Molecular Cloud Using Velocity Gradients

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Abstract

The relative role of turbulence, magnetic fields, and self-gravity in star formation is a subject of intensive debate. We present IRAM 30 m telescope observations of the 13CO (1–0) emission in the Serpens G3–G6 molecular cloud and apply to the data a set of statistical methods. These include the probability density functions of column density and the velocity gradients technique. We combine our data with the Planck 353 GHz polarized dust emission observations and Herschel H2 column density. We suggest that the Serpens G3–G6 south clump is undergoing a gravitational collapse. Our analysis reveals that the gravitational collapse happens at volume density $n \geq 10^3$ cm$^{-3}$. We estimate the plane-of-the-sky magnetic field strength to be approximately 120 $\mu$G using the traditional Davis–Chandrasekhar–Fermi method and 100 $\mu$G using a new technique proposed in Lazarian et al (2020). We find that the Serpens G3–G6 south clump’s total magnetic field energy significantly surpasses kinetic energy and gravitational energy. We conclude that the gravitational collapse could be successfully triggered in a supersonic and sub-Alfvénic cloud.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar magnetic fields (845); Interstellar dynamics (839); Star forming regions (1565)

1. Introduction

Star formation in molecular clouds is regulated by a combination of MHD turbulence, magnetic fields, and self-gravity over scales ranging from tens of parsecs to $<0.1$ pc (Jokipii 1966; Shu 1977, 1992; Shu et al. 1994; Kennicutt 1998a, 1998b; McKee & Ostriker 2007; Li & Henning 2011; Hull et al. 2013; Caprioli & Spitkovsky 2014; Andersson et al. 2015). A number of observational and numerical studies suggest that the interaction of turbulent supersonic flows and magnetic fields produces high-density fluctuations that serve as the nurseries for new stars (Nakamura et al. 1999; Tilley & Pudritz 2003; McKee & Ostriker 2007; Federrath 2013; Shimajiri et al. 2019; Hu et al. 2020c). However, the balance between the three is still obscured. In particular, it is challenging to identify the gravitational collapse, i.e., where gravity takes over.

To get insight into self-gravity in molecular clouds, the column density probability density functions (PDFs) are popularly used. In nongravitationally collapsing isothermal supersonic environments, the PDFs appear as a log-normal distribution with its width controlled by the sonic Mach number and the driving of the turbulence (Passot & Vázquez-Semadeni 1998; Klessen 2000; Robertson & Kravtsov 2008; Federrath et al. 2010; Kritsuk et al. 2011; Collins et al. 2012; Padoan et al. 2017; Burkhardt 2018). Self-gravity, further, introduces a power-law tail at the high-density range (Robertson & Kravtsov 2008; Ballesteros-Paredes et al. 2011; Collins et al. 2012; Burkhardt 2018; Körtgen et al. 2019). The transition from log-normal PDFs to power-law PDFs can reveal the density threshold, above which the gas becomes gravitationally collapsing.

The velocity gradients technique (VGT; González-Casanova & Lazarian 2017; Yuen & Lazarian 2017a; Hu et al. 2018; Lazarian & Yuen 2018a, and reference therein) is a novel approach to study the magnetic fields, turbulence, and self-gravity in the interstellar medium (ISM). VGT is rooted in MHD turbulence theory (Goldreich & Sridhar 1995) and turbulent reconnection theory (Lazarian & Vishniac 1999). These theories revealed the anisotropic nature of turbulent eddies, i.e., the eddies are elongating along the local magnetic fields. The magnetic field direction, therefore, is parallel to the eddies’ semimajor axis. The gradients of velocity fluctuations, which are perpendicular to the semimajor axis, play the role of probing the magnetic fields (Cho & Vishniac 2000; Maron & Goldreich 2001; Cho et al. 2002). Because subsonic velocity and density fluctuations exhibit similar statistical properties, the density gradients (or intensity gradients) are also perpendicular to the magnetic fields (Yuen & Lazarian 2017b; Hu et al. 2019b). The above consideration is the basis on which the VGT was developed.

However, this perpendicular relative orientation between the gradients and magnetic fields can be broken by self-gravity. In the case of gravitational collapse, the gravitational force pulls the plasma in the direction parallel to the magnetic field producing the most significant acceleration. Because gradients are pointing to maximum changes, the velocity gradients are thus dominated by gravitational acceleration, being parallel to the magnetic fields (Yuen & Lazarian 2017b; Hu et al. 2019c, 2020c). For density gradients, the consideration is similar. The most significant accumulation of material happens in the direction of gravitational collapse so that the intensity gradients are parallel to the magnetic fields. This phenomenon has been observed in the molecular clouds Serpens (Hu et al. 2019c), G3.43+0.024 (Tang et al. 2019), and NGC 1333 (Hu et al. 2021a). This particular reaction with respect to

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4 Note that in supersonic turbulence, shocks can also change the relative orientation of density gradients and magnetic fields (Yuen & Lazarian 2017b; Hu et al. 2019b; Beattie et al. 2020).
self-gravity enables VGT to reveal regions of gravitational collapse and quiescent areas where turbulent motions, thermal pressure, and magnetic support dominate over gravitational energy.

The Serpens cloud, which is famous for its high star formation rate (Cambresy 1999) and the high surface density of young stellar objects (YSOs; Eiroa et al. 2008), serves as an excellent object to study gravitational collapse. In particular, the Serpens G3–G6 region (Cohen & Kuhi 1979) is relatively isolated and does not have nearby H II regions or obvious large-scale gas shocks, both of which can cause changes in the alignment between magnetic fields, velocity gradients, and density gradients (Yuen & Lazarian 2017b; Hu et al. 2019b; Beattie et al. 2020; Hu et al. 2020a). Our study, therefore, focuses on the Serpens G3–G6 region. The $^{12}$CO (21) and $^{13}$CO (21) emission lines of this region were previously observed with the Arizona Radio Observatory Heinrich Hertz Submillimeter Telescope (Burleigh et al. 2013) with angular resolution of $\approx 38''$. Our new $^{13}$CO (1–0) emission-line data obtained with the IRAM 30 m telescope complement previous observations and have a higher angular resolution ($\approx 23''/5$). These data, including the Herschel H$_2$ column density image (André et al. 2010) and the Planck 353 GHz dust polarization data (Planck Collaboration et al. 2020), were used in this study to resolve kinematic, magnetic, and gravitational properties for Serpens at scales $\lesssim 1$ pc. The kinematic property is directly measured from the emission-line width, while we use two different approaches to estimate either magnetic or gravitational properties. The magnetic field strength was estimated by both the Davis–Chandrasekhar–Fermi method (Davis 1951; Chandrasekhar & Fermi 1953) based on the polarization measurement and a new approach based on the values of sonic Mach number $M_A$ and Alfvén Mach number $M_{A*}$ (Lazarian et al. 2020). Also, we employ the PDFs and VGT to confirm the gravitationally collapsing nature of the Serpens G3–G6 cloud.

The paper is organized as follows. In Section 2, we give the details of the observational data used in this work, including data reduction. In Section 3, we describe the methodology and algorithms implemented in VGT. In Section 4, we present our results of identifying the gravitationally collapsing regions on the Serpens G3–G6 clump, and we analyze the dynamics of the clump. We give a discussion in Section 5 and a conclusion in Section 6.

2. Observations and Data Reduction

2.1. $^{13}$CO (1–0) Emission Line

We obtained a new $^{13}$CO ($J = 10$) fully sampled map of Serpens using the IRAM 30 m telescope (Carter et al. 2012). The observations were obtained in July 2020 using 16 hr of telescope time under average summer weather conditions (6 mm median water vapor). We covered a field of view (FoV) of $10' \times 40'$. The $^{13}$CO ($J = 10$) emission was observed using the EMIR receiver and the VESPA spectrometer using a bandwidth of 60 MHz at 0.092 MHz resolution ($\approx 0.212$ km s$^{-1}$). The half-power beamwidth (HPBW) at 110.201354 GHz is $\approx 23''/5$.

We used the on-the-fly scanning strategy with a dump time of 0.7 s and a scanning speed of $11''/s$ to ensure a sampling of three dumps per beam along the scanning direction, with the scanning direction reversed after each raster line (i.e., zigzag scanning mode). We covered the full FoV ($\approx 0.11$ square degrees) with 15 rectangular tiles (of 15 OTF scans each) along the decl. direction and 20 rectangular tiles (of 5 OTF scans each) along the R.A. direction, followed by a calibration measurement. The reference position (REF) was observed for 10 s after each raster line following the pattern REFOTFOTFOFOFOTF–OTF–OTF–REF along the decl. direction and the pattern REFOTFOTFOFOFOTF–REF along the R.A. direction. Each tile is of approximately $8'' \times 40''$ size. In total, we employed about 13 minutes per tile.

Data reduction was carried out using the GILDAS1/CLASS software. The data were first calibrated to the $T_A$ scale and were then corrected for atmospheric absorption and spillover losses using the checker-wheel method (Penzias & Burbur 1973). A polynomial baseline of second order was subtracted from each spectrum, avoiding velocities with molecular emission. The spectra were then gridded into a data cube through convolution with a Gaussian kernel of FWHM $\sim 1/3$ of the IRAM 30 m telescope beamwidth at the rest line frequency. The typical ($1\sigma$) rms noise level achieved in the map is $0.33$ K per $212$ m s$^{-1}$ velocity channel. A large table of the individual spectra was made, and the spectra were finally combined to obtain a regularly gridded position–velocity data cube, setting the pixel size to $5''$. Here we convert the measured antenna temperature $T_A$ to brightness temperature $T_B$ through $T_B = (F_{eff}/B_{eff})T_A$, where $F_{eff} = 0.95$ is the forward efficiency of the IRAM 30 m telescope and $B_{eff} = 0.79$ is the main beam efficiency at 110.201354 GHz (Pety et al. 2017).

2.2. $^{12}$CO (2–1) and $^{13}$CO (2–1) Emission Lines

The $^{12}$CO (2–1) and $^{13}$CO (2–1) emission lines were observed with the Heinrich Hertz Submillimeter Telescope (Burleigh et al. 2013), while the H$_2$ column density data were obtained from the Herschel Gould Belt Survey (André et al. 2010). Each line was measured with 256 filters of 0.25 MHz bandwidth, giving a total spectral coverage of $41$ km s$^{-1}$ at a resolution of $0.33$ km s$^{-1}$. The angular resolution of the emission lines is $38''$ (0.04 pc) with a sensitivity of 0.12 K rms noise per pixel in one spectral channel (Burleigh et al. 2013). The radial velocity of the bulk of the emission ranges from about $-1$ to $+18$ km s$^{-1}$ for $^{12}$CO (2–1) and from $+2$ to $+13$ km s$^{-1}$ for $^{13}$CO (2–1) (Burleigh et al. 2013). We select the emissions within these ranges for our analysis.

2.3. Polarized Dust Emission

To trace the magnetic field orientation in the plane of the sky (POS), we use the Planck 353 GHz polarized dust signal data from the Planck 3rd Public Data Release (DR3) 2018 of the High Frequency Instrument (Planck Collaboration et al. 2020). The Planck observations define the polarization angle $\phi$ and polarization fraction $p$ through Stokes parameter maps $I$, $Q$, and $U$:

$$\phi = \frac{1}{2} \arctan(-U/Q),$$
$$p = \sqrt{Q^2 + U^2/I},$$

where $-U$ converts the angle from HEALPix convention to IAU convention, and the two-argument function arctan is used

http://www.iram.fr/IRAMFR/GILDAS

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3. Methodology: The Velocity Gradients Technique

3.1. Theoretical Consideration

VGT (González-Casanova & Lazarian 2017; Yuen & Lazarian 2017a; Hu et al. 2018; Lazarian & Yuen 2018a) is the main analysis tool in the work. It is theoretically rooted in the advanced MHD turbulence theory (Goldreich & Sridhar 1995, henceforth GS95), including the concept of fast turbulent reconnection theory (Lazarian & Vishniac 1999, henceforth LV99). These theories explained that turbulent eddies are anisotropic (see GS95) so that their semimajor axis is elongating along the local magnetic fields (see LV99). This was numerically demonstrated by Cho & Vishniac (2000) and Maron & Goldreich (2001). In particular, LV99 derived the anisotropy relation for the eddies in the local reference frame:

$$l_\parallel \approx L_{\text{inj}} \left( \frac{l_{\perp}}{L_{\text{inj}}} \right)^{2/3} M_A^{-4/3},$$

where $l_{\perp}$ and $l_\parallel$ are the perpendicular and parallel sizes of eddies with respect to the local magnetic field. $M_A$ is the Alfvén Mach number, and $L_{\text{inj}}$ is the injection scale of turbulence. The corresponding scaling of velocity fluctuation $v_l$ at scale $l$ is then

$$v_l \approx v_{\text{inj}} \left( \frac{l_{\perp}}{L_{\text{inj}}} \right)^{2/3} M_A^{1/3},$$

where $v_{\text{inj}}$ is the injection velocity. Explicitly, as the anisotropic relation indicates $l_{\perp} \ll l_\parallel$, the velocity gradients scale as (Yuen & Lazarian 2020)

$$\nabla v_l \propto v_l \approx v_{\text{inj}} \left( \frac{l_{\perp}}{L_{\text{inj}}} \right)^{2/3} M_A^{1/3},$$

which means that the smallest resolved eddies induce the largest gradients. The gradients are perpendicular to the local magnetic fields.

3.2. Principal Component Analysis

As we discussed above, the velocity fluctuation, i.e., the velocity variance, is related to the eddy’s size along the line of sight (LOS). Large velocity variance eddies give the most significant contribution to the velocity gradients. To get the largest velocity variance, Hu et al. (2018) proposed the principal component analysis (PCA) to preprocess the spectroscopic PPV cubes.

PCA treats the observed brightness temperature $T_b(x, y, v)$ in the PPV cube as the probability density function of three random variables $x$, $y$, $v$. By splitting the PPV cube into $n_v$ velocity channels along the LOS, the covariance matrix $S(v_i, v_j)$ and its corresponding eigenvalue equation are defined as

$$S(v_i, v_j) \propto \int dxdy T_b(x, y, v) T_b(x, y, v_j)$$

$$- \int dxdy T_b(x, y, v_j) \int dxdy T_b(x, y, v_j),$$

where $i, j = 1, 2, \ldots, n_v$ and $\lambda$ are the eigenvalues associated with the eigenvector $u$. The equation gives a total of $n_v$ eigenvalues. Each eigenvalue $\lambda_i$ is proportional to the squared velocity variance $v_i^2$ along the LOS. The velocity channel corresponding to the largest eigenvalue, therefore, has the most significant contribution to the velocity gradients.

In the frame of VGT, the PPV cube can be preprocessed by PCA in two different ways. The first one is treating the eigenvalues $\lambda$ as the weighting coefficients for each velocity channel (Hu et al. 2018). By integrating the weighted velocity channels along the LOS, we obtained the velocity centroid map $C(x, y)$:

$$C(x, y) = \frac{\int dv T_b(x, y, v) \cdot v \cdot \lambda(v)}{\int dv T_b(x, y, v)}.$$

Large eigenvalues enhance the significance of their corresponding velocity channels, while small eigenvalues give a suppression.

Alternatively, instead of weighting velocity channels, the PPV cube can be projected into a new orthogonal basis constructed by $n_v$ eigenvectors (Hu et al. 2020a). Its corresponding eigenvalue constrains the length of each eigenvector. Because the new axes are oriented along the direction of maximum variance, the PPV cube on a new basis exhibits the largest velocity variance. The projection is operated by the weighting channel $T_b(x, y, v_j)$ with the corresponding eigenvector element $u_{ij}$, in which the corresponding eigenchannel $I_i(x, y)$ is

$$I_i(x, y) = \sum_j^{n_v} u_{ij} \cdot T_b(x, y, v_j).$$

This step produces a total of $n_v$ eigenchannels in the eigenvector space. Generally, both the weighting and projecting approaches are figuring out the maximum velocity variance, which is the most important in velocity gradients’ calculation. In this work, we adopt the projection approach to construct the pseudo-Stokes parameters; see the discussion below.

Note here that the channel number $n_v$ should be sufficiently large so that the channel width $\Delta v$ satisfies $\Delta v < \sqrt{\delta(v^2)}$, where $\sqrt{\delta(v^2)}$ is the 1D velocity dispersion. We call the channel, which satisfies the criteria, a thin velocity channel. Due to the velocity caustic effect, which comes from the nonlinear mapping from real space to PPV space, the thin velocity channel’s intensity fluctuation is mainly induced by velocity fluctuations instead of density fluctuations (Lazarian & Pogosyan 2000). The thin velocity channels, therefore, record velocity information, which is used to calculate velocity gradients.
3.3. Subblock Averaging

The PPV cubes are preprocessed by PCA to extract the most crucial velocity components resulting in \( n_v \) eigenchannels. Each eigenchannel is convolved with \( 3 \times 3 \) Sobel kernels\(^7\) \( G_x \) and \( G_y \) to calculate pixelized gradient map \( \psi^i_{g}(x, y) \):

\[
\begin{align*}
\Delta_x L(x, y) &= G_x \ast L(x, y) \\
\Delta_y L(x, y) &= G_y \ast L(x, y) \\
\psi^i_{g}(x, y) &= \tan^{-1}\left( \frac{\Delta_x L(x, y)}{\Delta_y L(x, y)} \right),
\end{align*}
\]

where \( \Delta_x L(x, y) \) and \( \Delta_y L(x, y) \) are the x and y components of the gradient, respectively, and \( * \) denotes the convolution.

Note that the turbulent eddy discussed above is a statistical concept. A single gradient, therefore, does not necessarily correlate with the magnetic field. The orthogonal relative orientation between velocity gradients and the magnetic field appears only when the sampling is statistically sufficient. The statistical sampling procedure is proposed by Yuen & Lazarian (2017a), i.e., the subblock averaging method. First, the subblock averaging method takes all gradient orientations within a subblock of interest and then plots the corresponding histogram. A Gaussian fitting is then applied to the histogram. The Gaussian distribution’s expectation value is the statistically most probable gradient’s orientation within that subblock. Incidentally, the subblock averaging also partially suppresses the rms noise in the spectroscopic data.

The selection of subblock size, which controls the number of sampling points, is crucial. Hu et al. (2020c) later improved the subblock averaging method to be adaptive. The subblock centers were selected continuously, located at the position \((i, j), i, j = 1, 2, 3, \ldots \) etc. All gradients pixels within the rectangular boundaries \([i – d/2, i+d/2] \) and \([j – d/2, j+d/2] \) are selected to do averaging, where \( d \) is the subblock size. We vary the subblock size and check its corresponding fitting errors within the 95\% confidence level. When the fitting error reaches its minimum value, the corresponding subblock size is the optimal selection. We refer to this procedure as the adaptive subblock (ASB) averaging method (Hu et al. 2020c).

3.4. Pseudo-Stokes Parameters

By repeating the gradient’s calculation and ASB for each eigenchannel, we obtain a total of \( n_v \) eigengradient maps \( \psi^i_{g}(x, y) \) with \( i = 1, 2, \ldots, n_v \). In analogy to the Stokes parameters of polarization, the pseudo \( Q_g \) and \( U_g \) of gradient-inferred magnetic fields are defined as

\[
\begin{align*}
Q_g(x, y) &= \sum_{i=1}^{n_v} L_i(x, y) \cos(2\psi^i_{g}(x, y)) \\
U_g(x, y) &= \sum_{i=1}^{n_v} L_i(x, y) \sin(2\psi^i_{g}(x, y)) \\
\psi_g &= \frac{1}{2} \tan^{-1}\left( \frac{U_g}{Q_g} \right).
\end{align*}
\]

The pseudo polarization angle \( \psi_g \) is then defined correspondingly. Similar to the Planck polarization, \( \psi_B = \psi_g + \pi/2 \) gives the POS magnetic field orientation.

3.5. Alignment Measure

The relative alignment between magnetic fields orientation inferred from Planck polarization \( \phi_B \) and velocity gradient \( \psi_B \) is quantified by the alignment measure (AM; González-Casanova & Lazarian 2017):

\[
AM = 2 \left( \frac{\cos^2 \theta_r - \frac{1}{2}}{\theta_r} \right),
\]

where \( \theta_r = |\phi_B - \psi_B| \) and \( \theta_r \) denotes the average within a region of interest. The value of AM spans from \(-1 \) to 1. AM = 1 mean \( \phi_B \) and \( \psi_B \) are parallel, while AM = \(-1 \) indicates \( \phi_B \) and \( \psi_B \) are perpendicular. The standard deviation divided by the sample size’s square root gives the uncertainty \( \sigma_{AM} \).

3.6. Double-peak Histogram

The double-peak histogram achieves the detection of the gravitationally collapsing region. Unlike the gradients \( \psi_B \) in diffuse regions, the gravitational collapse flips the gradients by \( 90^\circ, \psi_B + \pi/2 \). The histogram of the gradients’ angle can be used to extract this change. In the diffuse region, the histogram exhibits a single Gaussian peak located at \( \psi_B \). The single peak of the histogram becomes \( \psi_B + \pi/2 \) in gravitationally collapsing regions. However, in transitional regions, which cover, for instance, half diffuse material and half gravitationally collapsing, the histogram is therefore expected to show two peak values of \( \psi_B \) and \( \psi_B + \pi/2 \). We call this type of histogram the double-peak histogram (DPH).

The DPH works as follows. Every single pixel of \( \psi_B \) is defined as the center of a subblock\(^8\) to draw the histogram. An envelope, which is a smooth curve outlining the extremes, is adopted for the histogram to suppress noise and the effect from insufficient bins. Any term whose histogram weight is less than the mean weight value of the envelope is masked. After masking, we work out the peak value of each consecutive envelope. Once more than one peak value appear and the maximum difference is within the range \( 90^\circ \pm \sigma_g \), where \( \sigma_g \) is the total standard deviation, the center of this second subblock is labeled as the boundary of a gravitationally collapsing region. The details of the algorithm are presented in Hu et al. (2020c).

4. Results

4.1. Integrated Intensity Map and \( \text{H}_2 \) Column Density Map

Figure 1 presents the \( \text{H}_2 \) column density map for the Serpens G3–G6 clump. The \( \text{H}_2 \) column density structures are elongated and filamentary. Here we plot the distribution of young stellar objects (YSOs) within this clump. The YSOs are identified by Harvey et al. (2007). The evolutionary stage of a YSO can be classified as (in order of youngest to oldest): Class I, flat, Class II, and Class III (Lada 1987; Andre & Montmerle 1994; 2007).

\(^7\) Note that this subblock is different from the ASB, which is used to determine the mean gradients’ orientation. The second subblock implemented in the DPH is used to extract the change of gradients. The second subblock size can be different from the one for the ASB. In this work, we adopt the second subblock size of \( 30 \times 30 \) pixels, which are statistically sufficient (Hu et al. 2020c).
Greene et al. 1994). We find Class I and flat YSOs concentrate on the south dense clump core and the northeast filamentary tail. Class II YSOs are mainly located at the north filamentary tail, while Class III only occupies a small fraction. YSOs’ high surface density at the dense clump core and the north tail indicates these two regions are actively forming stars.

The $^{13}$CO (1–0) emission line observed with the IRAM 30 m telescope zooms into the south dense clump with a resolution of $23''5 \approx 0.025$ pc; see Figure 2). The radial velocity of the emission ranges from about 2.6 to 12.0 km s$^{-1}$. The spectral line appears to have two apparent peaks: 2.22 K at 7.65 km s$^{-1}$ and 0.58 K at 4.9 km s$^{-1}$. After fitting a double Gaussian profile to the integrated spectral line shown in Figure 2, we obtain the 1D velocity dispersion $\sigma_1 = 1.1 \pm 0.2$ km s$^{-1}$ for the dominating emission feature. Figure 2 also shows the integrated intensity maps for the south dense clump core of the dominating emission feature. Figure 2 also shows the integrated intensity maps for the south dense clump core of Serpens G3–G6. The integration of $^{13}$CO (1–0) considers pixels where the brightness temperature is larger than 0.9 K, which is about three times the rms noise level. The $^{13}$CO (1–0) emission lines cover a wider $0''60 \times 0''15$ area. The clump’s $^{13}$CO (1–0) is still filamentary, spanning from north to south.

Figure 3 shows representative velocity channels from the $^{13}$CO (1–0) emission-line data, averaged over 636 m s$^{-1}$. The intensity structures seen in the velocity channels do not appear filamentary. In particular, two distinct dense structures appear at 7.0 and 7.6 km s$^{-1}$. These structures suggest that the velocity caustic effect is significant, i.e., velocity fluctuations dominate the thin velocity channels (Lazarian & Pogosyan 2000).

4.2. Gravitationally Collapsing Regions Identified from PDFs

The column density PDFs are widely used to study turbulence and self-gravity in ISM. The PDFs in gravitationally collapsing isothermal supersonic turbulence follow a hybrid of log-normal distribution $P_{NL}(s)$ in the low-intensity range and power-law distribution $P_{PL}(s)$ in the high-intensity range (Robertson & Kravtsov 2008; Ballesteros-Paredes et al. 2011; Collins et al. 2012; Burkhart 2018; Körtgen et al. 2019):

$$ P_{NL}(s) = \frac{D}{\sqrt{2\pi} \sigma_t} e^{-\frac{(s-s_t)^2}{2\sigma_t^2}}, \quad s < S_t $$

$$ P_{PL}(s) = DCe^{s_t}, \quad s > S_t, $$

where $s = \ln(N/N_0)$ is the logarithm of the normalized column density $N$. $S_t$ is transitional density between the $P_{NL}$ and $P_{NL}$.

$s_0 = -\frac{1}{2}\sigma_t^2$ is the mean logarithmic density. The standard deviation $\sigma_t$ for magnetized turbulence is related to the sonic Mach number $M_s$, driving parameter $b$, and compressibility $\beta$ (Molina et al. 2012):

$$ \sigma_t^2 = \log \left( 1 + b^2 M_s^2 \frac{\beta}{\beta + 1} \right). $$

The turbulence-driving parameter $b = 1/3$ for purely solenoidal driving, while $b = 1$ for purely compressive driving. For a natural mixture of solenoidal and compressive driving, $b$ is $\approx 0.4$ (Federrath & Banerjee 2015; Federrath et al. 2016). Assuming $P_{NL}(s) + P_{PL}(s)$ is normalized, continuous, and differentiable, the coefficient $D$ and $C$ are (Burkhart et al. 2017; Burkhart 2018)

$$ D = \left( \frac{Ce^{S_t}}{-k} + \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{2S_t + \sigma_t^2}{s\sqrt{2}\sigma_t} \right) \right) $$

$$ C = e^{0.5k(s+1)\sigma_t^2}. $$

In Figure 4, we plot the H$_2$ column density PDFs for the entire Serpens G3–G6 clump. The PDFs are log-normal with dispersion $\sigma_t \approx 0.5 \pm 0.04$ until $S_t \approx 0.88$, which indicates the gas is gravitationally collapsing when its density is larger than $N = e^{3.5} N_0 \approx 1.02 \times 10^{22}$ cm$^{-2}$. This column density threshold reveals that the south dense clump is gravitationally collapsing. The characteristic slope $k$ of that power-law is $-2.40 \pm 0.17$. Also, we zoom into the south dense region (see the red box in Figure 4), which corresponds to the measured $^{13}$CO (1–0). The south dense clump’s PDFs are still the combination of $P_{NL}$ and $P_{PL}$. The transition density $S_t \approx 0.66$ and the characteristic slope $k = -1.95 \pm 0.26$ identified the same gravitationally collapsing regions as before. The characteristic slope is related to the cloud mean free-fall time, the magnetic fields, and the efficiency of feedback (Federrath & Klessen 2013; Girichidis et al. 2014; Burkhart et al. 2017; Guszejnov et al. 2018). For instance, $k = -2.40 \pm 0.17$ and $k = -1.95 \pm 0.26$ correspond to radial density distributions $\rho(r) \propto r^{-1.83 \pm 0.06}$ and $\rho(r) \propto r^{-2.03 \pm 0.14}$, respectively. The power-law slopes of the radial density distributions suggest that all the high-density gas have collapsed into isothermal cores $\rho(r) \propto r^{-2}$ (Shu 1977) and the star formation efficiency is in the range of 0%–20% (Federrath & Klessen 2013).

4.3. Magnetic Field Morphology Traced by VGT

In Figure 5, we present the results of the VGT analysis using the $^{12}$CO (2–1) and $^{13}$CO (2–1) emission-line data sets. We use the emission within the velocity ranges $[+1, +13]$ km s$^{-1}$ for calculation following the recipe presented in Section 3. Pixels with brightness temperature less than three times the rms noise level (0.4 K) are blanked out. We average the gradients over $20 \times 20$ pixels and smooth the gradients map $\psi_g$ (see Equation (10)) with a Gaussian filter with kernel width 1, i.e., over 5 pixels.

We also compare the magnetic field inferred from the Planck 353 GHz polarized dust signal data (FWHM $\approx 10'$), We regrid the Planck polarization further to achieve the same pixel size as

$g = \frac{1}{2}\frac{e^{s_t}}{\sqrt{2\pi} \sigma_t} (1 + \frac{1}{2} \text{erf} \left( \frac{2S_t + \sigma_t^2}{s\sqrt{2}\sigma_t} \right))$ (see Equation (11) in Federrath & Klessen 2013).
emission lines. The polarization vector is also averaged over 20 × 20 pixels to match the gradients map. We find that the resulting gradients of $^{12}$CO (2–1) have good agreement with the Planck polarization, showing AM = 0.69 ± 0.04. Several anti-alignment vectors appear in the south dense region and image boundary. It is likely that the dust polarization and the $^{12}$CO (2–1) emission probe different spatial regions. The optically thick tracer $^{12}$CO samples the outskirt diffuse region of the cloud with volume density $n \approx 10^2$ cm$^{-3}$, while dust polarization likely traces denser regions. The theory of radiative torque (RAT) alignment (see Lazarian & Hoang 2007; Andersson et al. 2015 for a review) predicts that dust grains can remain aligned at high densities, especially in the presence of embedded stars. This is in agreement with numerical simulations (Bethell et al. 2007; Seifried et al. 2019). Therefore, we expect that for $n \geq 10^3$ cm$^{-3}$, grains are aligned in the regions that we study. In addition, the low resolution (10′) of the Planck data also contributes to the misalignment. The VGT measurements from $^{12}$CO (2–1) give less alignment (AM = 0.41 ± 0.07) with the Planck polarization. In particular, the gradients become perpendicular to the magnetic field in the south dense region. As the south dense region is identified to be gravitationally collapsing by the PDFs (see Section 4.2), this change in the gradients’ direction suggests the presence of a gravitational collapse (see Section 3). Because the overall magnetic fields horizontally cross the clump, while the gradients are nearly vertical, the resolution effects do not change this conclusion.

We plot the histograms of the relative alignment between rotated gradients and the magnetic fields in Figure 6. The histogram based on the $^{12}$CO (2–1) data is more concentrated around 0, which means that two vectors are parallel. The distribution based on the $^{13}$CO (2–1) data, however, spreads all the way to $\pi/2$, which means that two vectors are perpendicular. Previous studies reported that the VGT results of the $^{13}$CO emission are more accurate than the ones derived using the $^{12}$CO emission when comparing with dust polarization (Hu et al. 2019a; Alina et al. 2020) in nongravitationally collapsing clouds. Here we find that the VGT of $^{12}$CO gives better alignment. It is likely because the gravitational collapse in the Serpens G3–G6 south clump happens in dense gas...
The 12CO emission samples more diffuse regions so that its gradients are less affected by self-gravity.

4.4. Gravitationally Collapsing Regions Identified from VGT

The comparison of VGT and Planck polarization directly reveals the region undergoing gravitational collapse. However, insufficient resolution in polarization measurements limits this approach in small-scale studies. For instance, our high-resolution 13CO (1–0) can measure the pixelized gradient up to 5″, which is 120 times higher than Planck’s resolution, 10″. Nevertheless, the double-peak histogram (see Section 3) extends the VGT to identify the gravitationally collapsing region independent of polarization measurements.

$n \geq 10^3 \, \text{cm}^{-3}$. The 12CO emission samples more diffuse regions so that its gradients are less affected by self-gravity.

In Figure 7, we present the gradients map and the identified gravitationally collapsing regions using the 13CO (1–0) emission line. In dense areas, we find that the gradients flip their direction by 90° compared with surrounding low-intensity regions. The DPH finds three separate gravitationally collapsing regions. The largest gravitationally collapsing region covers the one identified by the PDFs (see Figure 4) and covers parts of low-intensity regions. It is likely the VGT is sensitive to gravity-induced inflows, which also span to low-intensity regions, while the PDFs are detecting the already-formed cores. Also, the DPH covers partially diffuse regions so that the actual gravitationally collapsing area is slightly overestimated. Nevertheless, both the VGT and the PDFs reveal that the central clump is gravitationally collapsing.

Gravitational collapse usually shows a signature of infalling motions. Explicitly, an infall signature in a spectral line presents itself in the form of a red–blue asymmetry, generally with a diminished redshifted component (Walker et al. 1994; Myers et al. 1996). To search for the signature, we integrated the 13CO (1–0) emission in a velocity range of +3.0 to +7.0 km s$^{-1}$ for blueshifted gas, as the velocity of bulk motion is 7.65 km s$^{-1}$ (see Section 4). Redshifted gas is integrated in the velocity range of +8.3 to +12.0 km s$^{-1}$. In Figure 8, the blueshifted and redshifted gases are overlaid in the integrated intensity map of 13CO (J = 1–0). We can see the clump is dominated by blueshifted gas. In the high-intensity region, blueshifted and redshifted gases are overlapped, which indicates an infalling motion along the LOS.
4.5. The Overall Energy Budget of the Serpens G3–G6 South Clump

Through both PDFs and VGT, we confirm that the Serpens G3–G6 south clump is gravitational collapsing. Here we determine the dynamics of the clump, focusing on the energy balance. The measured and derived physical parameters are listed in Table 1.

The area $A$ of the south clump is measured with $^{13}$CO (1–0). We include all pixels where their integrated brightness temperature is above the mean value (see Figure 2). Adopting $415 \pm 25$ pc as the distance (Dzib et al. 2010), we find $A \approx 2.14$ (0.2) pc. The value in brackets indicates the uncertainty, which is the average of the upper bound and lower bound. Assuming a simple spherical geometry, we have the effective LOS distance $L \approx 1.65$ pc. The 1D velocity dispersion $\sigma_{v,1D} \approx 1.1$ (0.2) km s$^{-1}$ is measured from the $^{13}$CO (1–0) emission line (see Figure 2). $\sigma_{v,1D}$ contains the contribution from both turbulence velocity and shear velocity. The polarization dispersion $\sigma_\rho \approx 8.54$ (0.72) deg is obtained from the Planck 353 GHz polarization; see Figure 9. The mean H$_2$ column density $N_0 \approx 9.18(0.43) \times 10^{22}$ cm$^{-2}$.

From these physical parameters, we derive the total mass $M = 440.8 \ (45.79) \ M_\odot$ and volume mass density $\rho_0 = 8.42(0.55) \times 10^{-21}$ g cm$^{-3}$. Adopting $f = 0.5$, the total magnetic field strength $B$ is calculated from the Davis–Chandrasekhar–Fermi method (Davis 1951; Chandrasekhar & Fermi 1953), giving $B = f \sqrt{4\pi \rho_0 \sigma_{v,1D}} / \sigma_\rho = 119.88(24.35) \mu$G. Assuming a spherically homogeneous cloud, the corresponding total kinetic energy $E_K = 1.59(0.60) \times 10^{36}$ erg, total gravitational energy $E_G = -1.21(0.26) \times 10^{36}$ erg, and total magnetic field energy $E_B = 3.96(1.71) \times 10^{36}$ erg. The ratio of kinetic energy and gravitational energy $|E_K/E_G| \approx 1.31$. In particular, the magnetic field energy to kinetic energy and gravitational energy ratios are $|E_B/E_K| \approx 2.50$ and $|E_B/E_G| \approx 3.28$, respectively. The role of the magnetic field in the Serpens G3–G6 south clump is much more significant than turbulence and self-gravity.

Note that the kinetic energy and magnetic field energy may be overestimated, as the dispersion $\sigma_{v,1D}$ considers both turbulence velocity and shear velocity. The ratio $E_B/E_K$ after simplification is equivalent to $E_B/E_K = (2f^2)/(9\sigma_\rho^2)$, which is independent of $\sigma_{v,1D}$. Similarly, we have $|E_B/E_G| = (10f^2\sigma_{v,1D}^2)/(9\pi\sigma_\rho^2 G N_0 \mu_L m_H L)$. The overestimated $\sigma_{v,1D}$ leads to a stronger magnetic field and also an overestimated $|E_B/E_G|$. Nevertheless, here we have the ratio $|E_B/E_G| \approx 3.28$; it is unlikely that the velocity dispersion is overestimated by a factor of 2 at least so that $|E_B/E_G| \approx 1$. Therefore, we expect the estimated magnetic field to be indeed stronger than turbulence and self-gravity. The significant magnetic field energy suggests that the gravitational collapse can happen in a strong magnetic field environment, as numerically suggested by Hu et al. (2020c).

In addition, assuming the gas temperature $T \sim 10$ K (Draine & Lazarian 1998), we have the isothermal sound speed $c_s = 188$ m s$^{-1}$ and Alfvén speed $v_A = 3.69(0.75)$ km s$^{-1}$. The corresponding sonic Mach number $M_S$ and Alfvén Mach number $M_A$ are therefore 10.1 (1.80) and 0.52 (0.14), respectively. Also, we have the compressibility $\beta = 0.005$ (0.001). Recall that we have the measured PDF dispersion $\sigma_\rho = 0.55 \pm 0.05$ (see Figure 4). The turbulence-driving parameter $b$ can be derived from Equation (13):

$$b^2 = \frac{(c_s^2 - 1)}{M_S^2} \frac{\beta + 1}{\beta}$$

using our derived parameters, we get $b \approx 0.84$, which suggests the turbulence in the Serpens G3–G6 south clump is mainly driven by compressive force. The study in Federrath & Klessen (2012) shows that the supernova-driven turbulence is more effective in producing compressive motions and is expected to be more prominent in regions of enhanced stellar feedback. Therefore, supernovae in this region may contribute to the compressive driving force here. On the other hand, solenoidal motions are more prominent in the quiescent areas with low star formation activity. Intense star formation (i.e., gravitational collapse) can also contribute, although our analysis shows that the gravity-induced motions do not dominate over large volumes. The latter point requires further studies.

10 Note that in calculating total magnetic field energy, we use only the POS magnetic field component. The actual magnetic field energy can be more significant.

11 For strongly magnetized media, the reconnection diffusion, which is the consequence of turbulent reconnection (LV99), is important (Lazarian 2005; Santos-Lima et al. 2010, 2020; Lazarian et al. 2012).
4.6. Measuring Mean Magnetic Field Strength

The Planck measurement gives an overall view of the magnetic field. However, its resolution limits our scope to smaller scales. The dispersion of polarization measures only large-scale magnetic fields, so that its value may be underestimated. The smooth field lines on a large scale suggest this underestimation is not significant.

In addition to the DCF method, we also estimated the $M_\Lambda$ directly from velocity gradients using the new approach proposed in Lazarian et al. (2018b). It was shown that the properties of velocity gradients over the subblock are a function of $M_\Lambda$. In particular, the dispersion of the velocity gradients’ orientation was shown to exhibit the power-law relation with $M_\Lambda$, and a different power-law relation was obtained for the so-called “Top-to-Bottom” ratio of the thin channel velocity gradients’ (VChGs) distribution:

$$M_\Lambda \approx 1.6(T_v/B_v)^{1/(1.6-1)}, \quad M_\Lambda \leq 1$$

$$M_\Lambda \approx 7.0(T_v/B_v)^{1/(1.6-1)}, \quad M_\Lambda > 1,$$

where $T_v$ denotes the maximum value of the fitted histogram of the velocity gradient’s orientation, while $B_v$ is the minimum value. The analytical justification of these relations is provided in Lazarian et al. (2020). Here we, however, use the empirically obtained dependencies (Hu et al. 2019b). This new way of obtaining the Alfvén Mach number provides us an $M_\Lambda$ distribution map for the Serpens G3–G6 south clump, as shown in Figure 10. We find the median value of $M_\Lambda$ is 0.62 for

$\uparrow\uparrow$
the south clump. We also repeat the analysis for the $^{13}$CO (1–0) emission line and find the median value $M_A \approx 0.53$.

We note that the difference between evaluating $M_A$ using the new gradient approach in Lazarian et al. (2018b) and the traditional DCF method is that the new technique gets the value of $M_A$ over an individual subblock. Therefore, we get not a single value of $M_A$, but a distribution of magnetization of $M_A$ over the cloud image. Naturally, the new way of measuring magnetization is much more informative compared to measuring the dispersion of the projected magnetic field over the cloud image. This difference was demonstrated earlier in Hu et al. (2019c), where for a set of molecular clouds the polarization provided the mean value of magnetization and the distribution of velocity gradients provided the detailed maps of magnetization with the averaged value in good agreement with that obtained using polarization.

In the present study, we also have a similar situation. The average value of $M_A$ estimated by the new VGT approach is close to the value that is obtained by measuring the directions of polarization. The latter is $M_A = 0.52 \pm 0.1$. This

### Table 1

| Physical Parameter                          | Symbol/Definition | Value (uncertainty) | Reference |
|---------------------------------------------|-------------------|---------------------|-----------|
| Area                                        | $A$               | 2.14 (0.20) pc$^3$  | Measured  |
| 1D velocity dispersion                      | $\sigma_{v,1D}$   | 1.10 (0.20) km s$^{-1}$ | Measured  |
| Polarization dispersion                     | $\sigma_p$        | 8.54 (0.72) deg.    | Measured  |
| H$_2$ column density                        | $N_H$             | 9.18 (0.43) x $10^{21}$ cm$^{-2}$ | Measured  |
| Effective diameter                          | $L = 2\sqrt[3]{A/\pi}$ | 1.65 (0.08) pc     | Derived   |
| Effective radius                            | $R = L/2$         | 0.83 (0.04) pc      | Derived   |
| H$_2$ volume number density                 | $n_0 = N_0/L$     | 1800.2 (117.62) cm$^{-3}$ | Derived   |
| Mass of an H atom                           | $m_H$             | 1.67 x $10^{-24}$ g  | Ref.1     |
| Mean molecular weight                       | $\mu_{H_2}$       | 2.8                 | Ref.1     |
| Volume mass density                         | $\rho_0 = n_0\mu_{H_2}m_H$ | 8.42 (0.55) x $10^{-21}$ g cm$^{-3}$ | Derived   |
| Mass                                         | $M = N_0\mu_{H_2}m_H A$ | 440.8 (45.79) M$_\odot$ | Derived   |
| Magnetic field strength                     | $B = f\sqrt{\mu_0\sigma_{v,1D}/\sigma_p}$ | 119.88 (24.35) $\mu$G | Derived   |
| Kinetic energy                              | $E_k = 3M\sigma_{v,1D}^2/2$ | 1.59 (0.60) x 10$^{66}$ erg | Derived   |
| Gravitational energy                        | $E_g = -3GM^2/5R$ | $-1.21 (0.26) x 10^{66}$ erg | Derived   |
| Magnetic energy                             | $E_B = B^2R^3/6$  | 3.97 (1.71) x 10$^{66}$ erg | Derived   |
| Viral parameter                             | $\alpha_{vir} = |E_E/E_g|/2$ | 2.63 (1.14)             | Derived   |
| Free-fall time                              | $t_{ff} = \sqrt{3\pi/2(2G\mu_0)}$ | 0.73 (0.02) Myr | Derived   |
| Sound speed (isothermal)                    | $c_s = \sqrt{\mu_0 T/\mu_{H_2}m_H}$ | 188 m s$^{-1}$ | Ref.1 ($\mu_p = 2.33$) |
| Alfven speed                                | $v_A = B/\sqrt{\mu_0\rho_0}$ | 3.69 (0.75) km s$^{-1}$ | Derived   |
| 3D sonic Mach number                        | $M_{A,3D} = \sqrt{3\sigma_{v,3D}/c_s}$ | 10.1 (1.80)             | Derived   |
| 3D Alfven Mach number                       | $M_{A,3D} = \sqrt{3\sigma_{v,3D}/v_A}$ | 0.52 (0.14)             | Derived   |
| Compressibility                             | $\beta = 2(M_\mu_{H_2}A)^2$ | 0.005 (0.001) | Derived   |

**Note.** All physical parameters are derived for pixels that fall within the 28.68 K km s$^{-1}$ (mean intensity value) $^{13}$CO (1–0) intensity contours drawn in Figure 2. All uncertainties consider the error propagation among each physical parameter. The gas temperature $T$ is assumed to be 10 K (Draine & Lazarian 1998). The calculation of gravitational energy and magnetic energy assumes that the cloud is spherical and has a uniform density. Reference: (1) Kauffmann et al. (2008).

**Figure 9.** The histogram of the magnetic field angle obtained from Planck 353 GHz polarization. The angle is measured in IAU convention.

**Figure 10.** The histogram of $M_A$ estimated from the distribution of velocity gradients over a subblock (Lazarian et al. 2018b). The median values of $M_A$ are 0.62 and 0.53 for $^{13}$CO (1–0) and $^{13}$CO (2–1), respectively.
correspondence is important as the technique in Lazarian et al. (2018b) and the DCF-type measurements of $M_A$ are very different both in terms of the information employed and how this information is processed. This increases our confidence in our results.

Having $M_A$ in hand, one can use a new technique of measuring magnetic strength in Lazarian et al. (2020). The technique is termed MM2 there, as it uses the values of two Mach numbers, the sonic one $M_S$ and the Alfvén one $M_A$. Using the relation derived in Lazarian et al. (2020), one can evaluate the POS magnetic field as

$$B = \Omega c_s \sqrt{4\pi \rho_0 M_S M_A^{-1}}, \quad (17)$$

where $\Omega$ is a geometrical factor. By adopting $\Omega = 1$ (i.e., the magnetic field perpendicular to the LOS), $M_A = 0.62$ (i.e., measured by VGT), $M_S = 10.1$, $\rho_0 = 8.42 \times 10^{-21} \text{ g cm}^{-3}$, and $c_s = 188 \text{ m s}^{-1}$, we get $B \approx 100 \mu \text{G}$, which is close to the one ($\approx 120 \mu \text{G}$) derived from the DCF method.

5. Discussion

5.1. Tracing the Magnetic Field Direction with VGT

Measuring the magnetic field in molecular clouds is generally difficult. The polarization measurement is one practical approach to trace the magnetic fields. It is rooted in the theory of RAT alignment (Lazarian & Hoang 2007; Andersson et al. 2015), which predicts that the polarized dust thermal emission is perpendicular to the magnetic field and the polarized starlight is parallel to the magnetic fields. Through the measured dispersion of the dust polarization directions and the information on spectral broadening, one can estimate the magnetic field through the DCF method (Falceta-Gonçalves et al. 2008; Cho & Yoo 2016). However, the polarization only gives the integrated magnetic field measurement along the LOS.

To achieve the local magnetic field measurement in molecular clouds, several techniques, for instance, the correlation function analysis (CFA; Lazarian et al. 2002; Esquivel & Lazarian 2011), the structure function analysis (SFA; Hu et al. 2021b; Xu & Hu 2021; Hu & Lazarian 2021), and the more recent VGT (González-Casanova & Lazarian 2017; Yuen & Lazarian 2017a; Hu et al. 2018; Lazarian & Yuen 2018a), have been proposed. These techniques are based on the anisotropy of MHD turbulence, i.e., turbulent eddies are elongating along their local magnetic field direction (Goldreich & Sridhar 1995; Lazarian & Vishniac 1999). In particular, for VGT, the velocity gradients of eddies are perpendicular to their local magnetic fields so that the gradients reveal the direction of the magnetic fields. Compared with dust polarization, the VGT, used in this work, exhibits several advantages in tracing magnetic fields. First, it employs spectroscopic data to measure the molecular cloud’s local magnetic fields so that it gets rid of the contamination from the foreground (Lazarian & Yuen 2018a; Hu et al. 2020e; Lu et al. 2020). Using spectroscopic data and VGT, one can achieve a higher resolution of the resulting magnetic field map. Also, VGT can be applied to multiple emission lines to reveal how the magnetic field changes with the variation of density (Hu et al. 2019a; Hu & Lazarian 2021).

5.2. Identifying Gravitationally Collapsing Regions by VGT

Observationally identifying gravitationally collapsing regions is notoriously challenging. The column density PDFs provide one possible solution. In isothermal molecular clouds, the PDFs follow a log-normal distribution for nongravitationally collapsing gas. The self-gravity, however, introduces a power-law tail to the high-density range. This power-law tail statistically reveals the critical density threshold above which the gas becomes gravitational collapsing. In this work, we find the gravitationally collapsing gas corresponds to density $N_H \approx 1.02 \times 10^{22} \text{ cm}^{-2}$ in the Serpens G3–G6 clump.

VGT provides an alternative way to identify gravitational collapse. In turbulence-dominated diffuse media, the velocity gradients are perpendicular to the magnetic fields (Lazarian & Yuen 2018a). In the presence of gravitational collapse, the gravity-induced velocity acceleration changes the velocity gradients by $90^\circ$ being parallel to the magnetic fields (Yuen & Lazarian 2017b; Hu et al. 2020c). This change reveals the gravitationally collapsing regions. For instance, VGT confirms that the G3–G6 south clump is gravitationally collapsing here. In addition, utilizing different emission lines, VGT can tell us the volume density range in which the collapse occurs. As shown in Figure 5, the change of gradients appears only in the $^{13}\text{CO}$ map, which means the collapse happens at volume density $n \geq 10^3 \text{ cm}^{-3}$.

The application of VGT is not limited to nearby molecular clouds. Multiple molecular clouds and molecular filaments can be easily separated from spectroscopic PPV cubes. A complete survey of gravitationally collapsing clouds and filaments is achievable using abundant spectroscopic data sets, for instance, the JCMT (Liu et al. 2019), GAS (Kauffmann et al. 2017), COMPLETE (Ridge et al. 2006), FCRAO (Young et al. 1995), ThrUMMS (Barnes et al. 2015), CHaMP (Yonekura et al. 2005), and MALT90 (Foster et al. 2011) surveys.

5.3. Comparison with Density Gradients

In addition to velocity gradients, density gradients provide an alternative way to study the magnetic fields. For instance, Soler et al. (2013) used the histogram of relative orientation (HRO) to characterize the relative orientation of column density gradients and magnetic fields. The HRO technique relies on the polarimetry measurement to get magnetic field information.

The HRO should not be confused with the intensity gradient technique (IGT) which is the outshoot of the VGT (Hu et al. 2019b). The IGT can identify the direction of the magnetic field in subsonic turbulence and identify shocks in supersonic turbulence. Different from HRO, IGT is independent of polarimetry and keeps the spatial information of density gradients by employing the subblock averaging method, which was first implemented in VGT (Yuen & Lazarian 2017a).

Here we make a comparison of HRO and IGT using the Herschel and Planck data. A numerical comparison is presented in Hu et al. (2019b). For HRO, the density gradients were directly calculated for each pixel following the recipe proposed in Soler et al. (2013). The gradients were then segmented according to their corresponding column density value. After that, we draw the histogram of the relative angle $\theta$ between

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13 For some settings, we know that the turbulence is subsonic. This is the case, for instance, for clusters of galaxies (Hu et al. 2020b) where IGT was recently used to predict the POS magnetic field directions.
orthogonal alignment with the magnetic fields. At the high-density range, the $\varsigma$ of V-HRO drops dramatically to be negative and a flip in the velocity gradients’ direction occurs. As this change of direction is insensitive to shocks and can be amplified by the subblock averaging method, we therefore can identify gravitationally collapsing regions through velocity gradients (Yuen & Lazarian 2017b; Hu et al. 2020a, Hu et al. 2020c).

5.4. The Interaction of Turbulence, Magnetic Field, and Self-gravity in Star Formation

Star formation is the subject of hot debate in modern astrophysics. The present two classes of star formation theory differ in the role played by magnetic fields. Mestel & Spitzer (1956) first proposed the strong magnetic field model that clouds, which are mainly regulated by the magnetic fields, are formed with subcritical masses. The magnetic support can be removed if mass could move across field lines. This removal is mainly conducted by neutral gas through the process of ambipolar diffusion (Mestel 1966; Spitzer 1968). The ambipolar diffusion increases the mass to flux ratio. As a consequence, cloud envelopes are subcritical, and cloud cores are supercritical. It, therefore, leads to the low efficiency of star formation. This explanation assumes flux-freezing conditions of the magnetic field in the absence of turbulence. However, the turbulence is ubiquitous in the ISM (Armstrong et al. 1995; Chepurnov & Lazarian 2010; Xu & Zhang 2017; Zhang et al. 2020), and in the presence of turbulence, flux freezing no longer holds, as the process of fast turbulent magnetic reconnection breaks the magnetic freezing (Lazarian & Vishniac 1999). Based on the theory of turbulent reconnection, Lazarian (2005, 2014) and Lazarian et al. (2012) identified connection diffusion (RD) as an essential process of removing magnetic flux. Consequently, the total magnetic field may be larger than its viral value, while the region can still be contracting. The RD theory predictions were confirmed in Santos-Lima et al. (2010, 2012, 2013) for molecular clouds and circumstellar disk settings.13 It increases the mass to flux ratio and allows the magnetic field to equalize inside and outside the cloud, decreasing magnetic support. Unlike the ambipolar diffusion, which depends on the ionization, the reconnection diffusion is only related to the turbulent eddies’ scale and the turbulent velocities (Lazarian 2005). The weak magnetic field model (Mac Low & Klessen 2004; Padoan & Nordlund 1999) suggests that clouds are formed at the intersection of turbulent supersonic flows. This model requires supercritical clouds so that gravitational collapse can be triggered without removing magnetic support.

Our analysis reveals that the Serpens G3–G6 south clump is supersonic ($M_s = 10.1$) and sub-Alfvénic ($M_A = 0.52$). The ratio $\lambda$ between the actual and critical mass-to-magnetic flux ratios $M^2/B^2$ is (Crutcher 2004) $\lambda = 7.6 \times 10^{-22} N_{\text{H}}/B \approx 0.58$. $\lambda < 1$ suggests the cloud is subcritical. Also, the total magnetic field energy in the Serpens G3–G6 south clump significantly surpasses the sum of total kinetic energy and gravitational energy (see Table 1), suggesting the magnetic field is relatively strong in this gravitationally collapsing clump.

The typical strong magnetic field model ignores the turbulence effect. Consequently, it is difficult to accumulate enough gas along the field to overcome the magnetic field.

13 The quantitative tests of the theoretical predictions related to the violation of flux freezing and reconnection diffusion in a turbulent fluid can be found in Eyink et al. (2013) and Santos-Lima et al. (2020).
(Mestel & Spitzer 1956). However, turbulent compression can contribute to material accumulation. Because the strong magnetic fields provide pressures perpendicular to the field lines, the compression preferentially follows the magnetic fields and accumulates material along the perpendicular direction. Once the collapse is triggered, the inflows also predominantly move along the field lines. Consequently, the gravitationally bound cloud will be thin oblate spheroids, as we see in Figure 2. Our results suggest compressive turbulence in the subcritical Serpens G3–G6 south clump. It supports the turbulent, strong magnetic field model.

Another observation of the Serpens south region’s magnetic field suggests that magnetic supercriticality sets in at visual extinctions larger than 21 mag, which also indicates that gravitational collapse can be triggered in a strongly magnetized environment (Pillai et al. 2020).

5.5. Uncertainty and Robustness

In this work, we use the DCF method to estimate the total magnetic field strength. The DCF method assumes that (i) ISM turbulence is an isotropic superposition of linear small-amplitude Alfvén waves, (ii) turbulence is homogeneous in the region studied, (iii) the compressibility and density variations of the media are negligible, and (iv) the variations of the magnetic field direction and the velocity fluctuations arise from the same region in space. These assumptions could raise uncertainties in our estimation. Nevertheless, the direct measurement from Zeeman splitting reveals that the LOS magnetic field strength is \( B \approx 80 \mu G \) for H1 volume density \( n \approx 4 \times 10^4 \) cm\(^{-3}\) (Crutcher 2012). As the magnetic field is amplified in a gravitationally collapsing region, we expect that the uncertainties in our estimated POS magnetic field strength \( B \approx 120 \mu G \) from the DCF method and \( B \approx 100 \mu G \) from the MM2 method are not significant.

The measured velocity dispersion includes the contribution from both turbulent velocity and shear velocity. In our calculation, we did not separate the two components. As discussed in Section 4.5, the ratio between kinetic energy and magnetic energy is independent of the velocity dispersion. The uncertainty here mainly comes from the polarization measurement. The velocity dispersion gives contributions to the ratio of magnetic energy and gravitational energy. However, the overestimated velocity dispersion is unlikely to compensate for the difference so that the ratio is less than 1.

Also, we assume the gas temperature \( T \approx 10 \) K. This assumption introduces uncertainties to the calculation of sound speed and sonic Mach number. The gas temperature can be roughly estimated from the optically thick \(^{12}\)CO (2–1) emission line (Pineda et al. 2010; Kong et al. 2015):

\[
J_\nu(T) = \frac{h\nu/k_b}{\exp(h\nu/(k_BT)) - 1}
\]

\[
T = \frac{h\nu_{12}}{k_b} \left[ \log(1 + \frac{h\nu_{12}/k_B}{T_b^2 + J_s(T)b}) \right]^{-1}
\]

\[
= 11.06 \left[ \log(1 + \frac{11.06}{T_b^2 + 0.194}) \right]^{-1}
\]

(18)

where \( h \) is the Planck constant, \( \nu_{12} \) is the emission frequency of \(^{12}\)CO (2–1), \( k_b \) is the Boltzmann constant, \( T_b^2 \) is the peak intensity of \(^{12}\)CO (2–) in units of kelvin, \( J_s(T) \) is the effective radiation temperature, and \( T_{bg} = 2.725 \) K is the temperature of the cosmic microwave background radiation. By using a range of observed \( T_b \) values, we estimate that \( T \) ranges from 3.7 K to 14.3 K, with a median value of 7.1 K. A species at transition level \( J = 1–0 \) is brighter than the one at \( J = 2–1 \), so it would correspond to a higher temperature. We, therefore, expect that the assumption \( T = 10 \) K does not change significantly our conclusions.

6. Conclusion

The energy balance between turbulence, magnetic fields, and self-gravity is still obscured in the process of star formation. In this work, we target the Serpens G3–G6 clump to study its kinetic, magnetic, and gravitational properties. We employ several data sets, including CO isotopolog emission lines from the HHT and IRAM telescopes, \( \text{H}_2 \) column density data from the Herschel Gould Belt Survey, and dust polarization data from Planck 353 GHz measurement. Our main discoveries are:

1. Using the column density PDFs and the VGT method, we confirm that the Serpens G3–G6 south clump is gravitationally collapsing, which is in agreement with the observed high surface density of YSOs.

2. The VGT method reveals that the gravitational collapse in the Serpens G3–G6 south clump occurs at volume density \( n \geq 10^3 \) cm\(^{-3}\).

3. We confirm that the VGT method can trace the magnetic fields and identify gravitationally collapsing regions independently of polarization measurements.

4. We use the traditional DCF method and the new MM2 technique to calculate the POS magnetic field strength of the Serpens G3–G6 south clump. The magnetic field strengths estimated using the DCF method and the MM2 method are approximately 120 \( \mu G \) and 100 \( \mu G \), respectively.

5. We find that the magnetic field energy dominates the energy budget of the supersonic Serpens G3–G6 south clump and that the turbulence is mainly driven by compressive forces.

6. We conclude that the gravitational collapse can be successfully triggered in a supersonic and sub-Alfvénic environment.

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Software: Julia (Bezanson et al. 2012), Paraview (Ahrens et al. 2005), GILDAS1/CLASS (http://www.iram.fr/IRAMFR/GILDAS).
