GAS KINEMATICS AND THE DRAGGED MAGNETIC FIELD IN THE HIGH-MASS MOLECULAR OUTFLOW SOURCE G192.16−3.84: AN SMA VIEW

Hauyu Baobab Liu1, Keiping Qu2, Qizhou Zhang3, Josep M. Girart4, and Paul T. P. Ho1,3

1 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan
2 School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
4 Instituto de Ciências do Espaço (CIrão-IEEC), Campus UAB, Facultat de Ciències, CSIC, E-08193 Bellaterra, Catalonia, Spain

Received 2012 December 12; accepted 2013 May 14; published 2013 June 17

ABSTRACT

We report Submillimeter Array (SMA) observations of polarized 0.88 mm thermal dust emission and various molecular line transitions toward the early B-type (L∗ ∼ 2 × 105 L⊙) star-forming region G192.16−3.84 (IRAS 05553+1631). The peak of the continuum Stokes-I emission coincides with a hot rotating disk/envelope (SO2 rotational temperature Trot ∼ 84+18−13 K), with a north–south velocity gradient. Joint analysis of the rotation curve traced by HCO+ 4−3 and SO2 19−18 suggests that the dense molecular gas is undergoing a spinning-up rotation, marginally bound by the gravitational force of an enclosed mass M∗gas+dust ∼ 11.2−25.2 M⊙. Perpendicular to the rotational plane, a 100/cos(i) km s−1 (i = 63°) high velocity molecular jet and a 15−20 km s−1 expanding biconical cavity were revealed in the CO 3−2 emission. The polarization percentage of the 0.88 mm continuum emission decreases toward the central rotating disk/envelope. The polarization angle in the inner 2′′ (0.015 pc) disk/envelope is perpendicular to the plane of the rotation. The magnetic field lines, which are predominantly in the toroidal direction along the disk plane, are likely to be dragged by the gravitationally accelerated rotation.

Key words: evolution – ISM: individual objects (G192.16−3.84) – stars: formation

Online-only material: color figures

1. INTRODUCTION

The ultracompact (UC) H II region G192.16−3.84 (cf. Molinari et al. 1996) is a well studied B3 star-forming region at a distance of 1.52 kpc (Shiozaki et al. 2011).5 The associated 2.1 μm point source (Indebetouw et al. 2003) was found to be embedded in a dense molecular core, which contains 290 M⊙ within a 0.11 pc radius (Shepherd & Kurtz 1999). This source emanates a 50 M⊙ bipolar CO outflow extending 2.5 (1.1 pc) east and 1.5 (0.66 pc) west (Snell et al. 1990; Shepherd & Churchwell 1996; Shepherd et al. 1998), which created the biconical cavity (Hodapp 1994; Shepherd et al. 1998; Indebetouw et al. 2003). The bipolar outflow can be further traced by Hα, [S ii], and 4.5 μm emission knots up to ±4 pc away (Devine et al. 1999; Qiu et al. 2008).

Interferometric observations of the centimeter and the millimeter continuum emission toward the 2.1 μm source suggest the existence of circumstellar gas and dust with a total mass of 4−18 M⊙ within a 2″×1″ (3040 AU × 1520 AU) region (Shepherd & Kurtz 1999; Shepherd et al. 2001; Shiozaki et al. 2011). At the ≲700 AU scale, the Very Long Baseline Array and very long baseline interferometry (VLBI; Japanese VLBI Network (JVN) and VLBI Exploration of Radio Astrometry (VERA)) observations of the 22 GHz H2O maser suggested the Keplerian motion of the dense gas and the outward motion of the bipolar outflow (Shepherd et al. 2004; Imai et al. 2006; Shiozaki et al. 2011; see also Codella et al. 1996).

This source was selected for the Submillimeter Array (SMA) observations of dust polarization because it represents one of the clearest cases of a massive disk/outflow system similar to the low-mass star formation (Shu et al. 1987; see also Zhang et al. 1998; Cesaroni et al. 2005; Sridharan et al. 2005; Su et al. 2007; Keto & Zhang 2010 and references therein for another massive case: IRAS 20126+4104 at D = 1.7 kpc, M∗ = 7–10 M⊙). In addition, its bright thermal continuum flux at the 0.85 mm wavelength band (2.1 ± 0.63 Jy in the central 15″ area; Shepherd et al. 2004) fulfills the required signal-to-noise ratio. Observations of the dust polarization vectors will provide the complementary aspect of the relative importance of the magnetic field strength.

The observing parameters for the target G192.16−3.84 are introduced in Section 2. The observational results for G192.16−3.84 are presented in Section 3. A brief discussion is provided in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

We performed observations in the 0.88 mm wavelength band in the single receiver polarization mode using the SMA6 (Ho et al. 2004; Marrone 2006). The phase referencing and pointing center of the observations is R.A. = 15h58m13.549, decl. = 16°31′58″.0 (J2000). The primary beam size of these observations was 36″. The observations tracked the frequency of 345.796 GHz at window 22 in the upper sideband. The spectral channel spacing was 0.7 km s−1. More details about the observations are summarized in Table 1. The detected spectral lines in these observations are summarized in Table 2.

The absolute flux, passband, and gain calibrations were carried out using the MIR IDL software package. The typical SMA observations may be subject to up to 15% of uncertainty in absolute flux scales. The calibrations of the polarization leakage

5 Most literature assumed a distance of 2 kpc. Throughout this paper, we will update the quoted physical quantities according to the water maser parallax distance reported by Shiozaki et al. (2011).

6 The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica (Ho et al. 2004).
were therefore sensitive to a maximally detectable scale of the dynamic range, and has a higher noise level (see Figure 1).

$i_{13}CO^+ 4^–3 346.99834 42$

$i_{13}CN 4^–3 345.33976 41$

\[ \sim \]

continuum emission using the CASA software package. We averaged the line-free channels in the channel (i.e., the D-term calibration) were carried out using the MIRIAD software package. We averaged the line-free channels in the lower and upper 4 GHz side bands to generate the continuum emission jointly. We omitted analyzing the blended SO216\,\rightarrow\,13 and SO9\,\rightarrow\,8–87 lines.

(i.e., the D-term calibration) were carried out using the MIRIAD software package. We averaged the line-free channels in the lower and upper 4 GHz side bands to generate the continuum channels, and imaged the continuum emission jointly. We carried out the imaging of the Stokes-Q and the Stokes-U components using MIRIAD, and carried out the imaging of the spectral line emission and the Stokes-I component of the continuum emission using the CASA software package.

The minimum and maximum baselines of our observations are \( \sim 8\,\lambda \) and \( \sim 260\,\lambda \), respectively. Our SMA observations were therefore sensitive to a maximally detectable scale of \( \sim 15\,\prime \) (Wilner & Welch 1994). Image synthesis using the Briggs Robust 0 weighting for the data collected from these observations yields a synthesized beam of 1.3′×0.87′ (P.A. = 90°), and a root-mean-squares (rms) noise level of 110 mJy beam\(^{-1}\) (0.96 K) in each 0.7 km s\(^{-1}\) velocity channel; imaging using the naturally weighted visibilities yields a synthesized beam of 1.9′×1.4′ (P.A. = 96°), and an rms noise level of 78 mJy beam\(^{-1}\) (0.30 K) in each 0.7 km s\(^{-1}\) velocity channel.

3. RESULTS

3.1. Geometry

3.1.1. The 0.88 mm Continuum Emission

The SMA Stokes-I image (Figure 1) recovers 1.2 Jy of flux in the central 15′ area. The previous James Clerk Maxwell Telescope measurement of 2.1 ± 0.63 Jy in the central 15′ area (Shepherd et al. 2004) indicates that the SMA Stokes-I image is subject to 43±13% of missing flux (see also Section 2). The averaged intensity of the missing flux over the central 15′ area is 1.3–7.4 mJy beam\(^{-1}\), which is lower than 62% of the first contour level in Figures 1 and 2. We therefore argue that the observed geometry from the 0.88 mm continuum Stokes-I emission is only minimally affected by the missing flux issue. According to the spectral energy distribution reported by Shepherd et al. (2004), the 0.88 mm continuum emission is mainly contributed by the dust thermal emission, as well as the free–free emission from the ionized gas surrounding the central star. The \( \lesssim 1\,\prime \) scale UC H II region has already been detected in centimeter continuum emission (Hughes & MacLeod 1993; Shepherd & Kurtz 1999; Shepherd et al. 2001), peaking at 05\,58\,\,\,13:531, 16\,31\,\,\,58:29 (J2000). Based on the measured spectral index of 0.3 ± 0.07 (Shepherd et al. 2004) and the 1.5 mJy total flux at the 3.6 cm band (Shepherd & Kurtz 1999), we estimate that the free–free continuum emission contributes to 3.6–6.0 mJy at the 0.88 mm wavelength band. Compared with the first contour level of the dust thermal emission at 0.88 mm in Figures 1 and 2, the free–free continuum emission is negligible.

The SMA Stokes-I continuum image (Figures 1 and 2) shows a ~6′′ scale source, of which the emission peak (the G192 envelope, hereafter) at 5\,58\,\,\,13:535, 16\,31\,\,\,58:25 (J2000) is connected with an ~3′′ scale elongation toward the southeast. With the \( \gtrsim 1\,\prime \) angular resolution of our observations (Section 2), the peak of the 0.88 mm Stokes-I emission cannot be distinguished from the centimeter continuum peak.

3.1.2. Polarized Dust Emission

We detect significant polarized continuum emission toward the peak of the Stokes-I emission, and detect marginal polarized continuum emission at two positions located in the southeastern
The velocity integrated intensity map (i.e., moment 0 maps) of CO 3–2, overlaid with the 0.88 mm continuum image (robust 0 weighted). Dark contours show the robust 0 weighted 0.88 mm continuum image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 1\'3 \times 0\'86$), with the levels of 14 mJy beam$^{-1}$ (3$\sigma$) × $[-1, 1, 2, 4, 8, 16, 32]$. The cyan, blue, and red contours show the integrated CO 3–2 emission in the labeled velocity ranges (naturally weighted; $\theta_{\text{maj}} \times \theta_{\text{min}} = 1\'8 \times 1\'4$). The cyan contour levels are 2.0 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2, 3]$; the blue contour levels are 1.4 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2]$; the red contour levels are 1.2 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2]$. The systemic velocity is $\sim 5.8$ km s$^{-1}$ (see Section 3.2). The dashed circle indicates the 18$''$ radius of the primary beam. Contours are plotted only in the region encircled by the dashed circle. We plot the spectral profile of the high velocity CO 3–2 components in Figure 4. The velocity integrated intensity map of CO 3–2 (robust 0 weighted; $\theta_{\text{maj}} \times \theta_{\text{min}} = 1\'2 \times 0\'86$) in the intermediate velocity range ($[-19, 1]$ km s$^{-1}$ and $[11, 41]$ km s$^{-1}$) is shown by gray scale, while the channel maps in this velocity range is presented in Figure 3. (A color version of this figure is available in the online journal.)

Elongation. The $B$-field directions$^7$ at the peak of the Stokes-$I$ emission are aligned in the north–south direction. The $B$-field directions at the other two detections are roughly parallel to the southeastern elongation.

3.1.3. The CO 3–2 Line

The most significant structure detected in CO 3–2 is the biconical cavity walls, centering around the peak of the Stokes-$I$ emission (Figure 2). The channel maps of CO 3–2 show the east–west bipolar cavity walls (Figure 3), which is consistent with the earlier observations of CO 1–0 (Shepherd et al. 1998). There is no zero-spacing information available, and the CO 3–2 maps for the spatially extended cavity walls cannot constrain its column density. The CO 3–2 emission at the higher velocity ranges (e.g., $|\Delta v_{\text{hel}}| \gg 30$ km s$^{-1}$) shows redshifted (relative to the systemic velocity $5.8$ km s$^{-1}$; see also Section 3.2) gas west of the peak of Stokes-$I$ continuum emission, and shows blueshifted gas around and toward the east of the peak of Stokes-$I$ continuum emission. The spectra of the high velocity CO gas are presented in Figure 4.

The $[-109, -79]$ km s$^{-1}$ component of the CO 3–2 outflow is potentially contaminated by the CH$_3$OH 16$_{1,15}$−15$_{2,14}$ transitions. The derived CO 3–2 parameters for the high velocity gas are presented in Figure 4. The channel maps of CO 3–2 show the robust 0 weighted 0.88 mm continuum image (robust 0 weighted). Dark contours show the integrated CO 3–2 emission in the labeled velocity ranges (naturally weighted; $\theta_{\text{maj}} \times \theta_{\text{min}} = 1\'8 \times 1\'4$). The cyan contour levels are 2.0 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2, 3]$; the blue contour levels are 1.4 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2]$; the red contour levels are 1.2 Jy beam$^{-1}$ km s$^{-1}$ × $[1, 2]$. The systemic velocity is $\sim 5.8$ km s$^{-1}$ (see Section 3.2). The dashed circle indicates the 18$''$ radius of the primary beam. Contours are plotted only in the region encircled by the dashed circle. We plot the spectral profile of the high velocity CO 3–2 components in Figure 4. The velocity integrated intensity map of CO 3–2 (robust 0 weighted; $\theta_{\text{maj}} \times \theta_{\text{min}} = 1\'2 \times 0\'86$) in the intermediate velocity range ($[-19, 1]$ km s$^{-1}$ and $[11, 41]$ km s$^{-1}$) is shown by gray scale, while the channel maps in this velocity range is presented in Figure 3. (A color version of this figure is available in the online journal.)

$^7$ The magnetic field ($B$-field) direction should be perpendicular to the polarization direction (Lazarian 2007 and references therein).

| Component   | Mass ($10^{-3} M_\odot$) | Momentum ($10^{-5} M_\odot$ km s$^{-1}$) | Energy (10$^{44}$ erg) |
|-------------|--------------------------|------------------------------------------|------------------------|
| [71, 101]   | km s$^{-1}$              | 0.069                                    | 10                     | 0.16                    |
| [−69, −29]  | km s$^{-1}$              | 1.2                                      | 130                    | 1.4                     |
| [−109, −79] | km s$^{-1}$              | 0.28                                     | 68                     | 1.7                     |

Notes. The momentum and energy are corrected for the inclination angle of $i = 63^\circ$. The $[-109, -79]$ km s$^{-1}$ component is likely to be contaminated by other molecular lines (see Section 3.1), and therefore our estimates should be considered as an upper limit.

The moment and energy are corrected for the inclination angle of $i = 63^\circ$. The $[-109, -79]$ km s$^{-1}$ component is likely to be contaminated by other molecular lines (see Section 3.1), and therefore our estimates should be considered as an upper limit.
Figure 3. The velocity channel maps of CO 3–2 in the intermediate velocity range (robust 0 weighted). The red star marks the peak of the 0.88 mm continuum emission (R.A. 5'h58'm13.535, decl. 16°31'.58'.25). The gray-scale bar has the unit of Jy beam$^{-1}$ km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 4. The spectra of CO 3–2 centered at the location of the $[-109, -79]$ km s$^{-1}$ component (cyan), the $[-69, -29]$ km s$^{-1}$ component (blue), and the $[71, 101]$ km s$^{-1}$ component as shown in Figure 2. For each component, the spectrum is averaged in the region enclosed by the first contour levels in Figure 2. For comparison, we overplot the SO$_2$ 191–180 spectrum (scaled by a factor of 0.3) as a dotted line, and overplot the manually shifted SO$_2$ 191–180 spectrum of which the peak is $-93$ km s$^{-1}$ (dotted magenta). We overplot the 1.4 km s$^{-1}$ velocity resolution CO 3–2 spectrum for the $[-109, -79]$ km s$^{-1}$ component as a black solid line ($1\sigma \sim 38$ mJy beam$^{-1}$).

(A color version of this figure is available in the online journal.)
Figure 5. The velocity integrated intensity maps (i.e., moment 0 maps) of the detected molecular lines (gray scale and dark contours). The molecular species and their upper level energy are labeled. The H$^{13}$CN 4–3 line is blended with the hot core tracer SO$_2$ 13$2,12$–12$1,11$ (Table 2) and therefore shows the enhanced brightness toward the G192 envelope. Dark contour levels are 0.5 Jy beam$^{-1}$ km s$^{-1}$ × [1, 2, 4, 8, 16, 32, 64]. Cyan contours show the 14 mJy beam$^{-1}$ × [2, 16] levels of the 0.88 mm continuum emission (robust 0 weighted). Gray-scale bars have the unit of Jy beam$^{-1}$ km s$^{-1}$. All molecular line images in this figure are naturally weighted. (A color version of this figure is available in the online journal.)
[71, 101] km s\(^{-1}\) CO 3–2 emission from the G192 envelope by their averaged velocities (i.e., Momentum/Mass) implies dynamic timescales of 910 ± 250 yr and 220 ± 80 yr, respectively. The momentum supply rates from these two high velocity components are \(0.14 \times 10^{-3} M_\odot\) km s\(^{-1}\) yr\(^{-1}\) and \(0.045 \times 10^{-3} M_\odot\) km s\(^{-1}\) yr\(^{-1}\), respectively. The summed momentum supply rate is \(\gtrsim 0.19 \times 10^{-3} M_\odot\) km s\(^{-1}\) yr\(^{-1}\), which is \(\sim 6.2\%\) of the momentum supply rate of the parsec scale CO outflow (Shepherd et al. 1998). Besides the two water maser sources (e.g., Shepherd et al. 2004), we are not sure whether there are other (proto)stars embedded in the G192 envelope. Deep JVLA observations to resolve the radio jet cores may allow us to see whether the high velocity molecular outflows are powered by a single dominant source.

### 3.1.4. Other Molecular Lines

The rest of the observed molecular lines trace a variety of morphology (Figure 5). The observed CH\(_3\)OH transition and the SO\(_2\) transitions mainly trace the G192 envelope and a compact component in the southeast of the G192 envelope. The high excitation SO\(_2\) line emission in the southeastern component may imply either a secondary source or the interaction between the outflow and the ambient gas. The H\(^{13}\)CO\(^+\) 4–3 and H\(^{13}\)CN 4–3 trace both the G192 envelope and the southeastern extension. The SO \(8\)–7 transition appears to trace the V-shape featured by the CO redshifted gas in the west of the G192 envelope, which can be associated with the innermost part of the cavity wall. Based on the integrated flux of the SO\(_2\) 41,1–32,2, 82,6–71,7, and 19,1–180 transitions in a \(R = 1.5\) circular region centered on the G192 envelope, assuming it is optically thin and in LTE, using the expression introduced in Fu et al. (2012), we constrain the rotational temperature in the G192 envelope to be \(T_{\text{rot}} \sim 84 \pm 13\) K.

### 3.2. Velocity Gradient in Dense Gas

The H\(^{13}\)CO\(^+\) 4–3 line generically traces the extended dense gas (Figure 5; Section 3.1). Gaussian fitting of the averaged spectrum of H\(^{13}\)CO\(^+\) 4–3 suggests that the systemic velocity of the dense gas is \(\sim 5.8 \pm 0.4\) km s\(^{-1}\). The comparison of the kinematics traced by the H\(^{13}\)CO\(^+\) 4–3 and SO\(_2\) 19,1–180,18 lines can provide clues to how the dense gas continues infalling into the inner disk/envelope.

Figure 6 shows the intensity-weighted averaged velocity maps (i.e., moment 1 maps) of SO\(_2\) 19,1–180,18 and H\(^{13}\)CO\(^+\) 4–3. The SO\(_2\) 19,1–180,18 transition traces a north–south velocity gradient in a \(\gtrsim 2\) region around the 0.88 mm Stokes-I peak. With the angular resolution of our observations, the resolved direction of the velocity gradient is consistent with the rotating plane of the disk/envelope reported by the water maser observations (Shepherd & Kurtz 1999; Shepherd et al. 2004; Imai et al. 2006). In a slightly bigger area, the H\(^{13}\)CO\(^+\) 4–3 line traces a northwest–southeast velocity gradient. The more extended gas shows the velocity close to the 5.8 km s\(^{-1}\) systemic velocity. The motion discussed here is also consistently traced by the other molecular lines presented in Figure 5.

Figure 7 shows the position–velocity (PV) diagrams of the H\(^{13}\)CO\(^+\) 4–3 and SO\(_2\) 19,1–180,18 lines. The PV cuts are centered at the peak of the continuum emission (\(58^\circ\)85’33’’ 13’’35’, 16’’31’’58’’25’’ (J2000)). The comparison of the SO\(_2\) 19,1–180,18 and H\(^{13}\)CO\(^+\) 4–3 PV diagrams at P.A. = 0° may imply an accelerated rotation of the warmer gas, which should lie closer to the embedded B3 star. The PV diagrams at P.A. = 130° show a bulk of blueshifted gas in the southeast (0°–5°). With the 0.7 km s\(^{-1}\) velocity resolution of our observations, we cannot resolve a clear trend of motion in that blueshifted gas component.

We jointly analyze the velocity field presented in the PV diagrams (P.A. = 0°) by applying the terminal velocity method (Sofue & Rubin 2001). This method defines the measured terminal velocity \(v_t\) by a velocity at which the intensity \(I\) equals

\[
I = \eta I_{\text{max}},
\]

where \(\eta\) is an adjustable parameter that can be optimized by checking the consistency of results from different molecular lines (e.g., Liu et al. 2010). We consider \(\eta = 0.2\) to be an optimal

![Figure 6](image-url)  
 Figure 6. The intensity-weighted average velocity maps (i.e., moment 1 maps) of SO\(_2\) 19,1–180,18 (robust 0 weighted) and H\(^{13}\)CO\(^+\) 4–3 (naturally weighted). The gray contours show the 14 mJy beam\(^{-1}\) \times [−1, 1, 2, 4, 8, 16, 32] levels of the 0.88 mm continuum emission (robust 0 weighted). Note that the scales of the upper and lower panels are different.

(A color version of this figure is available in the online journal.)
higher angular resolution. Water masers, or by observing the thermal dust continuum emission with 

8 Shepherd & Kurtz (1999) reported that the deconvolved 2.6 mm emission source has a position angle of −20°, and the water masers lines along the axis with −44° ± 21°. The exact orientation of the rotational axis is not yet known. This uncertainty may lead to the underestimates of the radii in Figure 8 by up to ∼30%. This issue can be resolved by observing the proper motion of the water masers, or by observing the thermal dust continuum emission with higher angular resolution.

Figure 7. The position–velocity (PV) diagrams of SO2 191−19−180,18 (robust 0 weighted; blue contours) and H13CO+ 4−3 (naturally weighted; gray scale and dark contours). The PV cuts are centered at the peak of the 0.88 mm Stokes-f continuum emission (S58813555, 16:31:58.25 (J2000)). The position angles of the PV cuts are labeled in the individual panels. Contour levels are 0.2 Jy beam−1 × [1, 2, 3, 4, 5, 6]. The dashed lines label the velocity $v_{\text{lsr}} = 5.8$ km s−1.

(A color version of this figure is available in the online journal.)

choice to analyze our data, which suppresses the confusion of gas from outer radii while guaranteeing that all pixels picked up by this method are above the 3σ detection level. We note that relative to the naive choice of $\eta = 1.0$, our choice of $\eta = 0.2$ would potentially overestimate the rotational velocity.

Figure 8 presents the $\eta = 0.2$ results up to a radius that the terminal velocity still can be distinguished from the systemic velocity 5.8 km s−1. By assuming the plane of rotation8 lies along the axis with P.A. = 0°, the measured terminal velocities within the 0.01 pc (1′36) radius are consistent with the inclined (i = 63°) Keplerian rotation, which is bound by the gravitational force of the embedded mass $M_{\text{gas+dust}} \sim 11.2–25.2$ $M_\odot$ (Shepherd & Kurtz 1999; Shepherd et al. 2001, 2004; Shiozaki et al. 2011). At the >0.01 pc radii, the steeper decline of the measured terminal velocities than the rotational velocities of the Keplerian models may indicate that the radial infall motion is not negligible in the more extended region (see the discussion in Tobin et al. 2012), although it is also consistent with the changes in the inclination angle. The previous Very Large Array observations of the 22 GHz water maser further traced the [−7, 16] km s−1 Keplerian rotation inward of the ∼0′25 (360 AU) radius (Shepherd & Kurtz 1999). These data consistently indicate the centripetally accelerated rotation toward the young star. Whether or not a Keplerian disk exists can be checked by the higher angular resolution observations.

Both Figures 7 and 8 present the spatial asymmetry of the brightness distribution and the velocity field in H13CO+ 4−3. The spatial asymmetry of the brightness distribution is consistent with the dust continuum image (Figure 1) that also shows a southeastern extension. However, we cannot rule out the possibility that the observed asymmetry of the velocity field

4. DISCUSSION

We observed the 0.88 mm polarized thermal dust emission and the molecular line emission which trace a range of excitation conditions toward the B3 star-forming region G192.16−3.84. The kinematics traced by the observed molecular lines as well as the previous detections of the 22 GHz water maser suggest a Keplerian motion of dense gas, continuing from the <0.02 pc radius to inward of the ∼290 AU radius. The magnetic field lines at 0.02−0.05 pc scale may have already been twisted by the rotational motion, such that the B-field directions are parallel to the plane of rotation. The high velocity molecular outflow is observed to be perpendicular to the rotational plane of the dense gas. Supposedly, the high velocity molecular outflow is driven by the magnetocentrifugal wind over the past $\gtrsim 10^5$ yr outflow dynamical timescale. The magnetic field lines at the sub-AU scale may still be organized in a way such that they can drive the east–west bipolar wind. We refer to Hull et al. (2013) for the discussion about the misalignment of magnetic fields and outflows in lower mass protostellar cores.

The lower polarization fraction at the Stokes-I continuum peak (Figure 1) can be explained by the blended magnetic field lines in the inner and outer radii (Tang et al. 2009; Frau et al. 2011; Padovani et al. 2012), though such an interpretation is not unique. This “de-polarization effect” can alternatively be explained by the difference in dust grain properties or grain alignment efficiency (Lazarian 2007), although the significance of this effect is not yet robustly argued by the SMA case studies. We tentatively explain the non detection of the polarized intensity $\sim 1″$ northwest and southeast of the Stokes-I continuum peak by the nearly parallel to line-of-sight orientation of the magnetic field lines dragged by the rotational velocity field. We note that the B-field morphology is essentially unresolved. In an
edge-on geometry, if the B field is pulled in by the contraction process, with an hour-glass morphology (e.g., Greaves et al. 1994; Girart et al. 2006, 2009; Rao et al. 2009), most of the unresolved B field lines will be aligned along the line-of-sight, or blended and canceled across the line of sight. The only remaining field detectable in such a case might be the field lines that exit from the top and bottom of the edge-on disk, and hence are aligned parallel to the disk. This would be an alternative to the scenario where the field lines are rendered toroidal by rotational motions. Figure 9 shows the schematic pictures for the proposed scenarios.

Our observations indicate that the B3 (proto)star embedded in G192.16−3.84 can form via a process similar to the scaled-up solar-mass-type star formation. With the sensitivity of the current instruments, observation with a large number of (fainter) samples is not yet possible. The proposed scenario is therefore subjected to the concern of target selection bias. Furthermore, in the environments of the more crowded OB clusters, whether or not the sources like G192.16−3.84 are representative remains an open question.

The SMA data were taken as part of the Large SMA Dust Polarization Survey (PI: Qizhou Zhang). We acknowledge the supports from the SMA staffs. H.B.L. thanks Vivien H.-R. Chen for useful discussions. J.M.G. is supported by the Spanish MINECO AYA2011-30228-C03-02 and the Catalan AGAUR 2009SGR1172 grants.

Facility: SMA

REFERENCES

Cesaroni, R., Neri, R., Olmi, L., et al. 2005, A&A, 434, 1039
Codella, C., Felli, M., & Natale, V. 1996, A&A, 311, 971
Devine, D., Bally, J., Reipurth, B., Shepherd, D., & Watson, A. 1999, AJ, 117, 2919
Frau, P., Galli, D., & Girart, J. M. 2011, A&A, 535, A44
Friedel, D. N., Snyder, L. E., Remijan, A. J., & Turner, B. E. 2005, ApJL, 632, L95
Fu, R. R., Mouillet, A., Patel, N. A., et al. 2012, ApJ, 746, 42
Girart, J. M., Beltrán, M. T., Zhang, Q., Rao, R., & Estalella, R. 2009, Sci, 324, 1408
Girart, J. M., Rao, R., & Marrone, D. P. 2006, Sci, 313, 812
Greaves, J. S., Murray, A. G., & Holland, W. S. 1994, A&A, 284, L19
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJL, 616, L1
Hodapp, K.-W. 1994, ApJS, 94, 615
Hughes, V. A., & MacLeod, G. C. 1993, AJ, 105, 1495
Hull, C. L. H., Plambeck, R. L., Bolatto, A. D., et al. 2013, ApJ, 768, 159
Imai, H., Omodaka, T., Hirota, T., et al. 2006, PASJ, 58, 883
Indebetouw, R., Watson, C., Johnson, K. E., Whitney, B., & Churchwell, E. 2003, ApJL, 596, L83
Keto, E., & Zhang, Q. 2010, MNRAS, 406, 102
Lazarian, A. 2007, JQSRT, 106, 225
Liu, H. B., Ho, P. T. P., Zhang, Q., et al. 2010, ApJ, 722, 262
Marrone, D. P. 2006, PhD thesis, Harvard Univ.
Molinari, S., Brand, J., Cesaroni, R., & Palla, F. 1996, A&A, 308, 573
Padovani, M., Brinch, C., Girart, J. M., et al. 2012, A&A, 543, A16
Qiu, K., Zhang, Q., Megeath, S. T., et al. 2008, ApJ, 685, 1005
Rao, R., Girart, J. M., Marrone, D. P., Lai, S.-P., & Schnee, S. 2009, ApJ, 707, 921
Shepherd, D. S., Borders, T., Claussen, M., Shirley, Y., & Kurtz, S. 2004, ApJ, 614, 211
Shepherd, D. S., & Churchwell, E. 1996, ApJ, 472, 225
Shepherd, D. S., Claussen, M. J., & Kurtz, S. E. 2001, Sci, 292, 1513
Shepherd, D. S., & Kurtz, S. E. 1999, ApJ, 523, 690
Shepherd, D. S., Watson, A. M., Sargent, A. I., & Churchwell, E. 1998, ApJ, 507, 861
Shiozaki, S., Imai, H., Tafoya, D., et al. 2011, PASJ, 63, 1219
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Snell, R. L., Dickman, R. L., & Huang, Y.-L. 1990, ApJ, 352, 139
Sofue, Y., & Rubin, V. 2001, ARA&A, 39, 137
Sridharan, T. K., Williams, J. S., & Fuller, G. A. 2005, ApJL, 631, L73
Su, Y.-N., Liu, S.-Y., Chen, H.-R., Zhang, Q., & Cesaroni, R. 2007, ApJ, 671, 571
Tang, Y.-W., Ho, P. T. P., Koch, P. M., et al. 2009, ApJ, 700, 251
Tobin, J. J., Hartmann, L., Bergin, E., et al. 2012, ApJ, 748, 16
Wilner, D. J., & Welch, W. J. 1994, ApJL, 427, 898
Zhang, Q., Hunter, T. R., & Sridharan, T. K. 1998, ApJL, 505, L151