The Circumstellar Disk of the B0 Protostar Powering the HH 80-81 Radio Jet

J. M. Girart\textsuperscript{1}, R. Estalella\textsuperscript{2}, M. Fernández-López\textsuperscript{3}, S. Curiel\textsuperscript{4}, P. Frau\textsuperscript{1}, R. Galvan-Madrid\textsuperscript{5}, R. Rao\textsuperscript{6}, G. Busquet\textsuperscript{1}, and C. Juárez\textsuperscript{1}

\textsuperscript{1} Instituto de Ciències de l’Espai (IEEC-CSIC), Can Magrans, S/N, E-08193 Cerdanyola del Vallès, Catalonia, Spain
\textsuperscript{2} Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (IEEC-UB), Martí Franquès 1, E-08028 Barcelona, Catalonia, Spain
\textsuperscript{3} Instituto Argentino de Radioastronomía, CCT-La Plata (CONICET), C.C.S. 1894, Villa Elisa, Argentina
\textsuperscript{4} Instituto de Astronomía, Universidad Nacional Autónoma de México (UNAM), Apartado Postal 70-264, 04510 México, DF, México
\textsuperscript{5} Instituto de Radioastronomía y Astrofísica (UNAM), 58089 Morelia, México
\textsuperscript{6} Instituto de Astronomía y Astrofísica, Academia Sinica, 645 N. Aohoku Place, Hilo, HI 96720, USA

Abstract

We present subarcsecond angular resolution observations carried out with the Submillimeter Array (SMA) at 880 \(\mu\)m centered at the B0-type protostar GGD27 MM1, the driving source of the parsec scale HH 80-81 jet. We constrain its polarized continuum emission to \(\lesssim0.8\%\) at this wavelength. Its submillimeter spectrum is dominated by sulfur-bearing species tracing a rotating-disk-like structure (SO and SO\(_2\) isopropologues mainly), but also shows HCN-bearing and CH\(_3\)OH lines, which trace the disk and the outflow cavity walls excavated by the HH 80-81 jet. The presence of many sulfurated lines could indicate the presence of shocked gas at the disk’s centrifugal barrier or that MM1 is a hot core at an evolved stage. The resolved SO\(_2\) emission traces the disk kinematics very well and we fit the SMA observations using a thin-disk Keplerian model, which gives the inclination (47\(^{\circ}\), the inner (\(\lesssim170\) au) and outer (\(\sim950–1300\) au) radii, and the disk’s rotation velocity (3.4 km s\(^{-1}\)) at a putative radius of 1700 au). We roughly estimate a protostellar dynamical mass of 4–18 M\(_{\odot}\). MM2 and WMC cores show, comparatively, an almost empty spectra, suggesting that they are associated with extended emission detected in previous low-angular resolution observations, and therefore indicating youth (MM2) or the presence of a less massive object (WMC).

Key words: ISM: individual objects (GGD27, HH 80-81, IRAS 18162-2048) – ISM: molecules – stars: formation – submillimeter: ISM

1. Introduction

It is well established that most low-mass stars develop accreting disks in their earliest stages previous to the premain-sequence phase (Adams et al. 1987; Shu et al. 1987; Butner et al. 1991; for the first HST images of disks, see O’Dell et al. 1993; O’Dell & Wen 1994; Burrows et al. 1996). These disks may be the seed by which planets are formed (see recent reviews by Helled et al. 2014 and Baruteau et al. 2014). The properties of the accretion disks are better studied by sulfur-bearing species tracing a rotating-disk-like structure (SO and SO\(_2\) isopropologues mainly), but also shows HCN-bearing and CH\(_3\)OH lines, which trace the disk and the outflow cavity walls excavated by the HH 80-81 jet. The presence of many sulfurated lines could indicate the presence of shocked gas at the disk’s centrifugal barrier or that MM1 is a hot core at an evolved stage. The resolved SO\(_2\) emission traces the disk kinematics very well and we fit the SMA observations using a thin-disk Keplerian model, which gives the inclination (47\(^{\circ}\), the inner (\(\lesssim170\) au) and outer (\(\sim950–1300\) au) radii, and the disk’s rotation velocity (3.4 km s\(^{-1}\)) at a putative radius of 1700 au). We roughly estimate a protostellar dynamical mass of 4–18 M\(_{\odot}\). MM2 and WMC cores show, comparatively, an almost empty spectra, suggesting that they are associated with extended emission detected in previous low-angular resolution observations, and therefore indicating youth (MM2) or the presence of a less massive object (WMC).

1. Introduction

It is well established that most low-mass stars develop accreting disks in their earliest stages previous to the premain-sequence phase (Adams et al. 1987; Shu et al. 1987; Butner et al. 1991; for the first HST images of disks, see O’Dell et al. 1993; O’Dell & Wen 1994; Burrows et al. 1996). These disks may be the seed by which planets are formed (see recent reviews by Helled et al. 2014 and Baruteau et al. 2014). The properties of the accretion disks are better studied in the T Tauri stage since the surrounding material has already infallen into the disk-protostar system or has been dispersed by the strong outflow activity (e.g., Hogerheijde et al. 1998; André et al. 2004). Still, recent works have found disks even in the earliest embedded stages of Class 0 protostars (e.g., Tobin et al. 2012; Murillo & Lai 2013; Rao et al. 2014). Class 0 disks are, in general, also smaller in size (\(\lesssim50\) au; e.g., Tobin et al. 2013; Segura-Cox et al. 2016) than T Tauri disks (200–300 au; e.g., Takakuwa et al. 2012; Harsono et al. 2014; Piétu et al. 2014). Disks are usually detected using their (sub)millimeter continuum emission and the emission of major CO isotopes. From the spectral line observations, the kinematical structure of disks around T Tauri protostars is found to be consistent with Keplerian motions (Guilloteau & Dutrey 1998; Guilloteau et al. 1999; Brinch et al. 2007; Lommen et al. 2008; Jørgensen et al. 2009; Schaefer et al. 2009; Takakuwa et al. 2012; Piétu et al. 2014), while it is more difficult to disentangle the kinematic signature of rotation and infalling motions in disks/envelopes of Class 0 protostars (Takakuwa et al. 2007; Brinch et al. 2009; Tobin et al. 2012).
high-angular resolution interferometric observations show evidence of the presence of an accretion disk surrounding the massive protostar (Fernández-López et al. 2011a, 2011b; Carrasco-González et al. 2012, hereafter FL11a, FL11b and CG12): a hot ($T \approx 150$ K) and very dense ($n(H_2) \approx 10^9$ cm$^{-3}$) molecular rotating disk-like structure with a radius of $\sim 0.5$ (850 au), with its rotation axes parallel to the radio jet, and surrounding a dusty disk with a radius of $\sim 0.15$ (200 au; FL11a, CG12). The estimated centrifugal radius, $\geq 650$ au (CG12), suggests that within the uncertainties the observed molecular and dusty rotating structure is an accretion disk. From the available observations, a dynamical mass (disk plus protostar) of $11 \pm 15 M_\odot$ and an accretion rate $\sim 10^{-4} M_\odot$ yr$^{-1}$ (FL11b, CG12) have been inferred.

In this paper, we present Submillimeter Array (SMA) observations carried out at 345 GHz at an angular resolution of $0.4''$. The observations are briefly described in Section 2 and the molecular line and dust continuum maps are presented in Section 3. An analysis of the kinematic behavior of the rotating disk-like structure from a selected sample of molecular line channel maps is shown in Section 4. In Section 5, we discuss the chemical and physical properties of the molecular gas detected with the SMA. Finally, in Section 6, we draw our main conclusions.

2. Observations

The SMA observations were taken on 2011 July 18 and October 3 in the extended and very extended configurations, respectively. The observations were done using the 345 GHz receivers and the quarter wave plates (QWP). During the observations, the QWP are rotated in order to measure the four circular polarization cross-correlations for each baseline, LL, RR, LR, and RL (R and L stand for right and left circular polarization). Marrone et al. (2006) and Marrone & Rao (2008) describe in detail the SMA polarimeter as well as the polarization calibration strategy. The receiver was tuned to cover the 332.1–336.0 and 344.0–347.9 GHz frequency ranges in the lower (LSB) and upper (USB) sidebands, respectively. The phase center of the telescope was pointing at $\alpha(J2000.0) = 18^h 19^m 12.10^s$ and $\delta(J2000.0) = -20^\circ 47' 30''$.00. The correlator provided a spectral resolution of about 0.8 MHz (i.e., 0.7 km s$^{-1}$ at 345 GHz). The gain calibrator was the QSO J1733–130. The bandpass and polarization calibrator was 3c454.3, which was observed in a parallactic angle range of $\sim 120^\circ$. The absolute flux scale was determined from observations of Callisto. The flux uncertainty was estimated to be $\sim 20\%$. The instrumental polarization was corrected at an accuracy level of $\pm 0.1\%$. The data were reduced using the MIRIAD software package (Wright & Sault 1993). The continuum and line molecular emission were separated in the visibility space using the MIRIAD task uvlin. An iterative process of phase-only self-calibration was performed using the continuum Stokes $I$ data. We started with a time interval of 20 minutes for the gain solutions. Then we decreased the interval in the subsequent steps until we reached an interval of 5 minutes. At the end of the self-calibration the rms noise decreased by about 30%. The derived gain solutions were applied to the molecular line data.

The continuum emission maps were obtained using the whole available bandwidth by setting a robust weighting of 0.5 and selecting the multi-frequency synthesis option in the MIRIAD task $\text{invert}$. The resulting synthesized beam full width at half maximum (FWHM) was $0''.48 \times 0''.35$ with a position angle of $29^\circ$. The achieved rms noise for the Stokes $I$ continuum map was 3.4 mJy beam$^{-1}$, and for the Stokes $Q$ and $U$ continuum maps was 1.6 mJy beam$^{-1}$. The larger rms noise of the Stokes $I$ is due to the limited dynamic range of the array. For the molecular line emission, channel maps were done using a robust weighting of 2.0 (equivalent to Natural weighting). This yielded synthesized beams sizes (FWHM, PA) between $0''.45 \times 0''.34$, $31^\circ$ and $0''.47 \times 0''.35$, $31^\circ$, which are the values for the lines with the highest and lowest frequencies, respectively. Figures were created using the GREG package (from the GILDAS7 software). The CO 3–2 maps from the observations presented here were already presented in Fernández-López et al. (2013).

3. Results

3.1. 880 $\mu$m Continuum Emission

Figure 1 shows the 880 $\mu$m (340.0 GHz) continuum map toward GGD27 obtained with the SMA. This map is in good agreement with the subarcsecond 1.35 mm continuum maps by FL11a, where the sources were detected. Table 1 shows the position, peak intensity, and flux density of the sources. MM1 shows compact emission. A Gaussian fit to this source yielded a deconvolved size of $\sim 0''.17$, indicating that the source radius is $\sim 150$ au, which is coincident with the upper limit found by FL11a. However, the fit cannot constrain whether the source is elongated in a particular direction. MM2(W) and MM2(E) are surrounded by weak emission at a $\sim 15$ mJy beam$^{-1}$ level extending $\sim 1''$ (about 1700 au). No dust continuum emission is

7. GILDAS data reduction package is available at http://www.iram.fr/IRAMFR/GILDAS.
detected around the warm molecular core (WMC; Qiu & Zhang 2009).

No continuum polarization is detected above the 3σ level in the Stokes Q and U maps. This yields an upper limit (at 3σ) of polarization of 0.8% and 4.7% for MM1 and MM2(W), respectively. The MM1 upper limit is significantly lower than the typical values found in millimeter interferometer observations of dense cores around low- and high-mass star-forming regions (∼2%–10%, e.g., Girart et al. 1999, 2006, 2009; Lai et al. 2003; Hull et al. 2014; Zhang et al. 2014), but it is not far from the values found in disks around low-mass young stellar objects (Hughes et al. 2013; Rao et al. 2014; Stephens et al. 2014; Kataoka et al. 2016).

3.2. Molecular Emission in MM1

Previous arcsecond observations show that in GGD27 there are three sites with bright molecular emission (e.g., Qiu & Zhang 2009): two of them are sites of massive star formation, GGD27 MM1 and MM2, and the WMC, which does not have clear signs of star formation. The new subarcsecond angular resolution observations over the whole observed spectra (totaling about 7.8 GHz) show very different molecular characteristics in the three molecular sources (see Figure 2). MM2 and WMC present an almost empty spectra, showing no emission lines in the whole spectrum except for the CO 3–2 line, and marginal emission of the SO 9–8, CH3OH 7–6/6–5 lines for WMC, and of the H13CO+ 4–3 line for MM 2. This is different to what has been found previously at lower angular resolution and lower frequencies, especially toward WMC, where several relatively complex molecules were previously detected, e.g., CH3OH, CH3CN, or HNCO (Qiu & Zhang 2009). MM2 exhibits strong CO emission associated with molecular outflows being powered by embedded protostars (Fernández-López et al. 2013).

In contrast to these two sources, GGD27 MM1 shows many molecular transitions along the observed bandwidth (see Figures 2 and 3). The spectra are dominated by SO2 and SO isotopologues, as well as by CH3OH lines. Other lines detected are isotopologues of HCN, HC3N, and deuterated formaldehyde. The H13CO+ 4–3 line is marginally detected in absorption toward the dust emission and in emission in an elongated structure east of the MM1 (the spectra of these two features are shown in Figure 4). Table 2 lists the parameters of the lines detected in MM1: line transition, frequency, line strength, energy level, and integrated flux of the detected molecular transitions. The integrated flux was obtained by adding the emission for the channels where the emission is detected and over a region of ∼2 arcsec2 on GGD27 MM1.

In order to better study and characterize the morphology and the kinematics of the detected molecular lines toward MM1, we present here channel maps of representative molecular lines (Figure 3), the zero- and first-order moment maps (integrated emission and velocity field weighted by intensity, respectively; Figure 5), and the position–velocity moment maps (integrated emission and velocity field weighted by position, respectively; Figure 6). For these high-excitation CH3OH lines (161,13–152,14, 182,16–173,14, and 191,19–182,15), and most of the detected 34SO lines (see the caption of Figure 3 for more details), the maps were combined in order to increase their signal-to-noise ratio. The three figures show that there is a distinctive velocity gradient along the major axis of the detected molecular disk-like structure (blueshifted and redshifted gas to the east and west, respectively). This velocity gradient is along the major axis of the molecular emission and perpendicular to the HH 80-81-RN radio jet. These properties are more clearly seen in the SO3, 34SO3, and 34SO lines. Indeed, the first-order moment maps of these lines are in agreement with those previously reported (FL11b, CG12), but the maps presented here resolve significantly better the velocity gradient. The emission along the major axis extends ∼1′′4 or 2400 au. The position–velocity cuts along the major axis also show a clear linear velocity gradient. The different lines of the SO3 main isotopologues show the same gradient within the uncertainties. However, the combination of 34SO2 lines show a steeper gradient and more compact emission. The peak emission also appears at higher velocities. The steeper velocity gradient is also seen in the 34SO line. The position–velocity cuts along the minor axis present a broader of the velocity range at the center for all the cases. All these features suggest that the emission traces a rotating molecular disk around the massive star, as previously suggested in FL11b and CG12.

The methanol emission appears to partially depart from the rotating disk pattern, which is clearly shown in the integrated emission and the velocity field of the CH3OH 71,7–61,6 A+ (Figure 5). The position–velocity cut along the major axis shows that whereas part of the emission arises from the rotating disk, there is a clear redshifted knot (peaking at vLSR = 16.0 km s−1) in the blueshifted side of the rotating disk (see Figure 6). Furthermore, the central channels of the CH3OH 71,7–61,6 A+ line shows that the emission is elongated along the jet axis (vLSR = 14.0 and 16.0 km s−1 channels in Figure 3). This suggests that not all the methanol emission is associated with the rotating disk, so some may arise from the walls of the cavity excavated by the outflow. The SO 8–7 line seems to be tracing both features, the rotating disk and the walls of the cavity. Finally, the HC15N 4–3 line does not clearly show the velocity gradient (see Figure 3), though this could be due to the low signal-to-noise ratio of the emission of this line.

4. Analysis: The Thin-disk Model for the SO2 and SO Emission

The SO2 and SO lines appear to show a clear velocity gradient along the major axis of the disk, suggestive of rotation, as observed previously at lower angular resolution (FL11b). To better constrain the kinematics of the disk, we modeled the emission with a rotating, geometrically thin disk, using the SO2 transitions 41,1–32,2, 82,2–71,7, 191,19–180,18, and 212,20–211,21; the 34SO 7–6 transition; and a sum of 33SO2 transitions for improving the signal-to-noise ratio.
The position angle of the projection of the disk axis on the plane of the sky (minor axis position angle) was fixed to 21°, which is the position angle of the radio jet (Martí et al. 1993). The inclination of the disk, \( i \), was defined as the angle between the disk axis and the line of sight (\( i = 0° \) for a face-on disk). We considered a rotation velocity given by a power law of the radius, \( v_r(r/r_0)^{q_r} \), where \( r_0 \) is an arbitrary reference radius \( (r_0 = 1°) \) and \( v_r \) is the rotation velocity at the reference radius. We assumed that the molecular emission arises from an area of the disk between an inner radius \( r_i \) and an outer radius \( r_o \).

We computed, for each point of a regular grid on the plane of the sky, the projection of the rotation velocity of the corresponding point of the disk along the line of sight \( v_z \). A Gaussian line profile of width \( \Delta v \) and centered on \( v_z \) was added to the channels associated with the grid point. The intensity of the Gaussian was taken to follow a power-law dependence on the disk radius, \( I(r) \). Finally, each channel map was convolved spatially with a Gaussian beam of width \( \Delta \theta \). However, the intensity scale of the channel maps is arbitrary. A scaling factor, the same for all channel maps, was obtained by minimizing the sum of the squared differences between the data channel maps and the synthetic channel maps. The model depends on a total of 11 parameters, namely the beamwidth, \( \Delta \theta \); the linewidth, \( \Delta v \); the disk center position, \( (x_0, y_0) \); the disk systemic velocity, \( v_0 \); the disk inner and outer radii, \( r_i \) and \( r_o \); the radial dependence power-law index of the intensity, \( q_i \); the projection of the disk rotation velocity at the reference radius, \( v_z \); the radial dependence power-law index of the rotation velocity, \( q_r \); and the disk inclination angle, \( i \).

Some of the parameters are known beforehand, such as \( \Delta \theta \), the synthesized beamwidth for every transition. Some others were taken as fixed: the rotation power-law index was taken as that of a Keplerian rotation, \( q_r = -0.5 \); and the intensity power-law index, which takes into account the radial dependence of density and temperature, was taken as \( q_i = -1 \).

The fitting procedure was the sampling of the multidimensional parameter space, using the same procedure as that described in Girart et al. (2014) and Estalella (2017). The parameter space was searched for the minimum value of the rms fit residual. Once a minimum of the rms fit residual was found, the uncertainty in the parameters fitted was found as the increment of each of the parameters of the fit necessary to increase the rms fit residual a factor of \( (1 + \Delta(m, \alpha)/(n - m))^{1/2} \), where \( n \) is the number of data points fitted, \( m \) is the number of parameters fitted, and \( \Delta(m, \alpha) \) is the value of \( \chi^2 \) for \( m \) degrees of freedom (the number of free parameters and \( \alpha \) is the significance level (\( \alpha = 0.68 \) for 1σ uncertainties).

The fit was performed in two steps. In a first run, the eight free parameters \( (\Delta v, x_0, y_0, v_0, r_p, r_o, v_z, i) \) were fitted simultaneously for the six transitions. From this run, we obtained the weighted average of the best-fit values for the parameters that do not depend on the transition, \( \Delta v, x_0, y_0, v_0, v_z, i \) and \( i \) (see Table 3). The value obtained for the disk inclination was \( i = 47° \pm 8° \). The projection of the rotation velocity at \( r_0 = 1° \) obtained is \( v_z \sin i = -2.5 \pm 0.5 \text{ km s}^{-1} \), corresponding to a deprojected rotation velocity \( v_\text{rot} = -3.4 \pm 0.8 \text{ km s}^{-1} \).

In a second run, we set as constant the eight parameters obtained from the first fit and we fitted the inner and outer radii of the disk for every transition. The results obtained are shown in Table 4. The inner radius obtained for all the transitions was \( r_i < 0.01 \). The outer radius for the \( \text{SO}_2 \) transitions is \( r_o \simeq 0.075 \), while for the \( ^{34}\text{SO} \) and \( ^{34}\text{SO}_2 \) transitions it is smaller,

---

**Figure 2.** Spectra toward GGD27 over the observed bandwidth. The four panels show the different frequency ranges covered by the LSB and USB. For each panel, the top, middle, and bottom spectra are taken at the MM 1, MM 2, and WMC positions. All of these spectra were averaged over a region of about 2 arcsec. The conversion factor from Jy to K is ∼6.5. The line with an “a” label is the \(^{34}\text{SO} \) 10\( \rightarrow \)10. The lines with a “b” label are \(^{34}\text{SO} \) 17\( \rightarrow \)17, \(^{34}\text{SO} \) 17\( \rightarrow \)17, and \(^{34}\text{O} \) 15\( \rightarrow \)15. The lines with a “c” label are CH3OH 18.\( \rightarrow \)17, and CH3OH 18.\( \rightarrow \)17.
Figure 3. Channel maps toward GGD27 MM1 of a representative set of molecular transitions. The molecular line transition is indicated in the right part of each row. CH$_3$OH 400 K indicates the stacking averaged map of a combination of three methanol lines with an energy level of the lower state of $\sim 400$ K (16,15=15,14, 18,16=17,15, and 19,18=18,16). Similarly, the $^{34}$SO$_2$ row is the result of stacking a combination of the detected $^{34}$SO$_2$ lines, (except for the 6,2=6,1 and 7,4=3,3 lines). These lines have energies, for their lower levels, between 54 and 162 K. The magenta contour emission in the top row shows the radio jet emission at 3.6 cm from (Carrasco-González et al. 2010). Contours are multiple of 2$\sigma$, with the first positive/negative contour at $\pm 2$-$\sigma$ level. The rms noise, $\sigma$, for each row of panels (from top to bottom): 64, 42, 70, 61, 74, 75, 23, and 65 mJy beam$^{-1}$. The red cross marks the position of GGD27 MM1 dust continuum source. The red solid and dashed lines indicate the orientation of the disk and jet, respectively.
5. Discussion

5.1. Rotating Disk-like Structure and the Stellar Mass

The analysis of the velocity field derived from the SO$_2$ and SO show that the emission is more compact in their $^{34}$S isotopologues and in the transition of the main SO$_2$ isotopologue with the highest energy level $(202.20-212.12)$. This is a consequence of the increase of the column density and temperature toward the center of the disk. However, the analysis of the velocity field derived from the SO$_2$ and SO isotopologues is limited by the signal-to-noise of the data (the highest value is $\approx15$). This precludes the detection of the faint gas at higher velocities, which is expected to arise closer to the protostar (according to the model, gas has intensities below the detectability of our data). Thus, our data cannot discern whether the rotation is Keplerian. However, the dynamical mass of the system (protostar and disk) can be constrained by using two approximations. First, we assume that the velocity in the whole disk is Keplerian ($M = \nu^2 \cdot r / G$). Taking the obtained rotation velocity (3.4 km s$^{-1}$) at the reference radius $r_0 \approx 0'55$. Figure 7 shows, as an example of the obtained fits, the channel maps for the SO$_2$ 4$_{3,1}-3_{2,2}$ and 19$_{1,19}-18_{1,18}$ transition data and their best-fit model. Figure 8 shows the position–velocity cut of the SO$_2$ 4$_{3,1}-3_{2,2}$ line and the best-fit model along the major axis.

Table 2

| Molecular transition | $\nu$ (GHz) | $E_i$ (K) | $S_{1/2}$ | $\int f_{	ext{mol}} d\nu$ (Jy km s$^{-1}$) |
|----------------------|-------------|-----------|----------|----------------------------------|
| SO$_2$ 4$_{3,1}-3_{2,2}$ | 332.50524 | 15.34 | 6.92 | 15.56 ± 0.64 |
| SO$_2$ 13$_{12}-12_{11}$ | 345.33854 | 76.41 | 13.41 | 13.82 ± 0.58 |
| SO$_2$ 16$_{15}-16_{14}$ | 346.52388 | 147.83 | 22.30 | 21.77 ± 1.15 |
| SO$_2$ 19$_{1,19}-18_{1,18}$ | 346.65217 | 151.50 | 41.98 | 21.03 ± 0.58 |
| 21$_{1,20}-21_{2,11}$ | 332.09143 | 203.59 | 15.20 | 13.00 ± 0.61 |

Notes.

$^a$ SO$_2$ 13$_{12}-12_{11}$ and H$^{13}$CN 4–3 are blended. The same holds for SO 9$_2$–8$_1$ and SO$_3$ 16$_{15}-16_{14}$. Therefore, their estimated line intensities are possibly not well determined and the quoted uncertainties come just from the fitting procedure.

$^b$ Tentative detection.

$^c$ Very broad line; the cloud velocities are strongly affected by missing flux.

$^d$ Tentative detection seen in absorption.

(1$''$ ≈ 1700 au), we estimate a dynamical mass of $22 \pm 4 M_\odot$. In second place, we assume that the gas is not all in Keplerian motion but still gravitationally bound. In this case, we can still
balance the gravitational and the kinetic energy of the gas at the outer edge of the disk \( (r_0 \sim 0''75 \simeq 1300 \text{ au}) \) and \( v_{\text{rot}} = \Delta v / (2 \sin i) = 2.3 \text{ km s}^{-1} \) to derive a dynamical mass \( (M = v^2 / (2G)) \) of \( 8 \pm 2 M_\odot \). With the present data, we cannot discern whether the Keplerian approximation stands for all the observed gas surrounding MM1 or there is a centrifugal barrier separating a rotating infalling region (outer disk/envelope) from a Keplerian rotating region (inner disk), as found in some lower mass protostars (Sakai et al. 2014). In any case, the latter value of \( 8 M_\odot \) is similar to that derived previously in (FL11b), where the virial assumption was used as

**Table 3** Thin-Disk Model: Weighted Average of Best-fit Parameters for All Transitions

| Parameter            | Units           | Value     |
|----------------------|-----------------|-----------|
| Linewidth \( \Delta v \) | (km s\(^{-1}\)) | 3.3 \pm 0.3 |
| Disk center \( x_0 \) | (arcsec)        | -0.13 \pm 0.05 |
| Disk center \( y_0 \) | (arcsec)        | -0.40 \pm 0.04 |
| Disk central \( v_0 \) | (km s\(^{-1}\)) | 12.4 \pm 0.2 |
| Rotation vel. \( v_\sin i^a \) | (km s\(^{-1}\)) | -2.5 \pm 0.5 |
| Disk inclination \( i \) | (degrees)       | 47 \pm 8 |

**Figure 5.** Moment 0 (integrated intensity) images from different molecular lines toward GGD27 MM1 (contours) overlapping its moment 1 (centroid velocity) images (color scale). The red cross marks the position of GGD27 MM1 dust continuum source. The dashed red and solid black lines indicate the orientation of the jet and disk, respectively. Labels with the name of the lines are placed at the bottom of every panel.

**Figure 6.** Position–velocity cuts along the major axis of the GGD27 MM1 disk (left panels; PA = 111\(^\circ\)) and minor axis (right panels; PA = 21\(^\circ\)) for several lines (solid black contours and gray scale). For comparison, all panels are overlapped with the SO\(_2\) 8\(_{2,6}-7_{1,7}\) line in red contours. Contours are in steps of \( 2\sigma \), starting at \( 2\sigma \). The rms noise of the different lines are given in Figure 3 except for the SO\(_2\) 8\(_{2,6}-7_{1,7}\), which is 74 mJy beam\(^{-1}\).

\(^a\) At the reference radius \( r_0 = 1''\).
well. From the dust emission at 1.36 mm, and assuming optically thin emission, the mass from the disk is \( \approx 4 M_\odot \) (FL11a). This suggests that the stellar mass should be between 4 and 18 \( M_\odot \). Therefore, the stellar mass is loosely constrained from the velocity analysis. The bolometric luminosity of this source is also not well constrained, but should be between 3300 \( L_\odot \) and \( 2 \times 10^3 L_\odot \) (FL11b). This is because there is contamination from other sources at mid- to far-infrared wavelengths (e.g., Aspin et al. 1991; Aspin & Geballe 1992; Qiu et al. 2008) and, in particular, from the nearby massive MM2 (FL11b). However, the range of values for masses is compatible with the possible values of the bolometric luminosity because a significant fraction of the luminosity comes from accretion (Yorke & Sonnhalter 2002; Hosokawa et al. 2010).

### 5.2. Chemical Composition of the MM1 Rotating Disk-like Structure

Despite having an observed rich spectrum, MM1 has a less rich chemistry than standard hot cores. The spectrum is dominated by sulfurated molecules and the lines that more clearly trace the rotating disk are SO and SO isotopologues, but also \( \text{H}_2\text{CO} \) (FL11b). Previous observations also show that CH\(_3\)CN, OCS, and HNCO are also bright in MM1 (Qiu & Zhang 2009), but the limited angular resolution of these data prevents us from confirming whether their emission arises from the rotating disk.

Girart et al. (2013) observed almost the same frequency range as the one presented here toward the DR 21(OH) massive star-forming region. The DR 21(OH) SMA 6 and SMA 7 submillimeter sources, known to be very dense hot cores, show the same lines detected in MM1. In these two hot cores, there are other molecular species that show emission as bright as the \( ^{34}\text{SO}_2 \) lines, specially methyl formate (\( \text{CH}_3\text{OCHO} \)), but also dimethyl ether (\( \text{CH}_3\text{OCH}_3 \)), formic acid (HCOOH), nitrogen monosulfide (NS), methanimine (\( \text{CH}_2\text{NH} \)), and ethyl cyanide (CH\(_2\)CH\(_2\)CN).

None of these molecules are detected toward MM1. The molecular emission associated with MM1 arises from hot, 120–160 K, and very dense gas (FL11b), excluding the possibility that the difference between DR 21(OH) and MM1 is due to a different excitation conditions. Thus, the lack of complex molecules in MM1 indicates a chemical differentiation with respect to the DR 21(OH) hot cores.

Recent observations toward disks around protostars show that the SO molecule is an excellent probe of the shocks generated at the position of the centrifugal barrier (Sakai et al. 2014; Oya et al. 2016). The centrifugal barrier is the transition region between the envelope and the rotationally supported disk, where most of the kinetic energy of the infalling envelope is converted into rotational energy (Sakai et al. 2014, 2016). Furthermore, chemical models predicts that not only SO but also SO\(_2\) are enhanced in shocks with moderate shock velocities (few \( \text{km s}^{-1} \)) generated in dense molecular environments, \( n(\text{H}_2) \sim 10^4–10^5 \text{ cm}^{-3} \) (Pineau des Forêts et al. 1993). Indeed, these two species are enhanced in shocks associated

---

**Table 4** Thin-disk Model: Disk Inner and Outer Radii Fitted for Every Transition

| Transition | Inner Radius (arcsec) | Outer Radius (arcsec) |
|------------|-----------------------|-----------------------|
| SO\(_2\) 4\(_{1,1}–3\_{2,2}\) | 0.04 ± 0.01 | 0.74 ± 0.01 |
| SO\(_2\) 8\(_{2,6}–7\_{,7}\) | 0.04 ± 0.01 | 0.75 ± 0.01 |
| SO\(_2\) 19\(_{1,19}–18\_{,18}\) | 0.04 ± 0.01 | 0.82 ± 0.01 |
| SO\(_2\) 2\(_{12,21}–2\_{11,21}\) | 0.09 ± 0.01 | 0.69 ± 0.01 |
| \(^{34}\text{SO} 7\_{2,8}–6\_{,7}\) | 0.03 ± 0.01 | 0.54 ± 0.01 |
| \(^{34}\text{SO}_2\) | 0.00 ± 0.01 | 0.59 ± 0.01 |

---

**Figure 7.** Channel maps of the SMA SO\(_2\) 19\(_{1,19}–18\_{,18}\) and the combined \(^{34}\text{SO}_2\) lines (first and third column, respectively). Best-thin-disk models for these two lines are shown in the second and fourth columns. These maps have been rotated 21° so the major and minor axes are the \( x \) and \( y \) axes, respectively.

**Figure 8.** Position–velocity cut along the major axis for the SO\(_2\) 4\(_{1,1}–3\_{2,2}\) line (contour map) and the best disk model for this transition (gray scales). Contours are in steps of 2\( L_\odot \), starting at 2\( L_\odot \).
with molecular outflows (Bachiller & Pérez Gutiérrez 1997; Codella et al. 2003; Podio et al. 2015).

Alternatively, the apparently sulfated dominated chemistry of the rotating disk-like structure around MM1 could be a consequence of MM1 being more evolved than the typical massive hot molecular cores (e.g., Charnley 1997; Minh 2016). Indeed, a chemical study of different species found that most molecules that are abundant in the hot molecular phase have their abundances decreased in UCHII phase, but this decrease is not so significant in some sulfated molecules such as SO and SO_2 (e.g., Gerner et al. 2014). In the case of SO_2, the UV photodissociation of the water, yielding OH, can enhance this molecule through the SO+OH → SO_2 reaction (Charnley 1997; Tappe et al. 2008; Qiu & Zhang 2009). In MM1, the source of UV radiation may arise from the strong shocks generated in the powerful jet (Carrasco-Gonzáleze et al. 2010), which would illuminate the surface of the molecular disk. A comparison between the spectral energy distribution of four massive cores without HII regions found that GGD27 MM1 appears to be the most evolved one (Herpin et al. 2009). We speculate that the spectral features of GGD27 MM1 indicate that this source is on the verge of forming an ultracompact (UC) HII region.

5.3. The Outflow Cavity Walls

As noted in Section 3, the spatial distribution of the CH_3OH emission partially departs from the expected pattern for the rotating molecular disk. This is better seen in the first-order momentum map (Figure 5) and in the position–velocity cuts (Figure 6). In this latter figure, there is an emission feature at v_{LSR} = 14.5 km s^{-1} just east of the disk center that does not follow the rotation pattern. The clump appears in the northern side of the blueshifted side of the rotating disk-like structure. This clump is also clearly seen in the SO 8_{o–7}_e emission. This feature along with the overall morphology of the CH_3OH, with the emission extended along the radio jet direction, suggests that the emission from CH_3OH is tracing the outflow cavity walls (the outflow is probably atomic and ionized since no high velocity CO emission is detected at these scales, see Fernández-López et al. 2013). The SO emission, along with the H_2CO 3_{1,2} − 2_{1,1} line emission (FL11a), appears to arise from both the rotating disk and the outflow cavity walls.

5.4. The Lack of Molecular Emission Associated with MM2 and WMC

The lack of molecular emission associated with MM2 and WMC may seem surprising, especially when they have bright 1 mm molecular emission at an angular resolution of 3′′ (Qiu & Zhang 2009). These observations showed that WMC and, to a lesser extent, MM2 are prominent in lines of CH_3OH, CH_3CN, H^13CO, SO, OCS, and HNCO with upper energy levels of <100 K. In contrast, none of the higher excitation lines detected in MM1 are detected in these two sources (Qiu & Zhang 2009, FL11a). This is because of the lower temperature (≈40 K) of these two sources. Thus, given the high volume density of MM2, ~ 10^9 cm^{-3}, one should expect to detect the SO and CH_3OH lines with similar energy levels and line strength as those detected at 1 mm, such as the CH_3OH 7_{1,7}−6_{1,6} A^{+} transition (see Table 2). But these are barely detected only in WMC. The rms in brightness temperature of our observation is about 4–5 K, so we are sensitive (at 3σ) to line intensities of ≥12–15 K. This indicates that the molecular gas around these two sources is extended and, in addition, since the upper limits for the brightness temperature are significantly lower than the gas kinetic temperature, the observed molecular lines are optically thin.

The SO_2 lines represent a different scenario, since they have not been detected toward WMC and MM2 at lower angular resolution and frequency (Qiu & Zhang 2009, FL11a). In this case, Qiu & Zhang (2009) interpreted this as a chemical differentiation because of their different evolutionary stages. MM2 has a similar mass as MM1 but it has a lower average volume density because it is more extended (FL11a). This is an indication that MM2 is possibly younger, suggesting that the accreted mass to this young stellar object is still smaller or that the accretion rate is not as high as in MM1. The WMC could be a less massive object than MM1 and MM2 because of the non-detection of the dust continuum emission.

6. Conclusions

We present subarcsecond angular resolution observations carried out with the SMA at 880 μm toward the GGD27 system. We do not detect any polarized continuum emission and place upper limits for the polarized intensity on GGD27 MM1 (≤ 0.8%) and GGD27 MM2 (≤ 4.7%). The MM1 spectrum is dominated by the presence of several sulfur-bearing species tracing the disk-like structure (SO and SO_2 isotopologues mainly), but it also shows HCN-bearing and CH_2OH lines. The CH_3OH and SO emission is in part tracing the disk rotation, but also comes from the cavity walls of the outflow excavated by the jet. H^13CO is seen in absorption against the MM1 continuum emission. We discuss that the abundance of sulfated lines in the spectrum (which is not common in other massive hot cores) could indicate the presence of shocked gas at the disk’s centrifugal barrier or that MM1 is a hot core at an evolved stage.

The 0′′4 SMA resolution allows us to clearly resolve the SO_2 disk’s kinematics. MM1 shows a velocity gradient along the disk’s major axis, which is steeper for the ^34SO_2 and ^32SO_2 lines, since their emission is more compact than for the SO_2 lines. We make a fit to the SMA observations using a thin-disk Keplerian model, which fully characterizes the geometry of the disk. The results of our fit give an inclination of 47°, an inner radius of ≤0.7″ (≤170 au) and an outer radius between 0″55 (950 au) and 0″75 (1300 au), depending on the molecular tracer. We also constrain the radial velocity at a putative radius of 1700 au in 3.4 km s^{-1}. Using these results, the estimated protostellar dynamical mass of MM1 is 4–18 M_⊙.

Finally, we also detect molecular emission from the MM2 and WMC cores (MM2 is also resolved in continuum emission). They show in comparison with MM1 an almost empty spectra suggesting that they are associated with extended emission (detected in previous low-angular resolution observations), and therefore indicating the presence of a very young system (MM2), still in a very early stage of accretion, or and the presence of a less massive object (WMC).

We thank all members of the SMA staff that made these observations possible. 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. J.M.G., R.E., G.B., and C.J. are supported by the MINECO (Spain) AYA2014-57369-C3-grant. S.C. acknowledges support from DGAPA, UNAM, and CONACyT, México.
