THE L723 LOW-MASS STAR FORMING PROTOSTELLAR SYSTEM: RESOLVING A DOUBLE CORE

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ABSTRACT

We present 1.35 mm Submillimeter Array (SMA) observations around the low-mass Class 0 source IRAS 19156+1906, at the center of the LDN 723 (L723) dark cloud. We detected emission from dust as well as emission from H$_2$CO, DCN, and CN lines, which arise from two cores, SMA 1 and SMA 2, separated by 2.9″ (880 AU in projected distance). SMA 2 is associated with the previously detected source VLA 2. Weak SiO 5–4 emission is detected, possibly tracing a region of interaction between the dense envelope and the outflow. We modeled the dust and H$_2$CO emission from the two cores. The results from the modeling show that the cores have similar physical properties (density and temperature distribution) but that SMA 2 has a larger p-H$_2$CO abundance (by a factor of 3–10) than SMA 1. The p-H$_2$CO abundances’ findings are compatible with the value of the outer part of the circumstellar envelopes associated with Class 0 sources. SMA 2 is harboring an active multiple low-mass protostellar system and powering at least one molecular outflow. In contrast, there are no known signs of outflow activity toward SMA 1. This suggests that SMA 2 is more evolved than SMA 1. The kinematics of the two sources show marginal evidence of infall and rotation motions. The mass detected by the SMA observation, which traces scales of $\lesssim$1000 AU, is only a small fraction of the mass contained in the large-scale molecular envelope, which suggests that L723 is still in a very early phase of star formation. Despite the apparent quiescent nature of the L723, fragmentation is occurring at the center of the cloud at different scales. Thus, at $\approx$1000 AU, the cloud has fragmented in two cores: SMA 1 and SMA 2. At the same time, at least one of these cores, SMA 2, has undergone additional fragmentation at scales of $\approx$150 AU, forming a multiple stellar system.

Key words: ISM: individual (LDN 723) – ISM: molecules – radio lines: ISM – stars: formation

Online-only material: color figure

1. INTRODUCTION

L723 is an isolated molecular cloud located at a distance of 300 ± 150 pc (Goldsmith et al. 1984) and with a systemic velocity of $V_{LSR}$ $\approx$ 10.9 km s$^{-1}$ (Girart et al. 1997). It harbors a low-mass, Class 0, young stellar object, first identified by the Infrared Astronomical Satellite (IRAS), IRAS 19156+1906 (Goldsmith et al. 1984), with a bolometric luminosity of 3.4 L$_{\odot}$ (Dartois et al. 2005). The properties of the protostar in the IR to mm wavelength range have been the subject of several studies (Davidson 1987; Andrés et al. 1993; Pezzuto et al. 2002; Dartois et al. 2005). IRAS 19156+1906 is associated with a CO outflow with a quadrupolar morphology (Goldsmith et al. 1984; Moriarty-Schieven & Snell 1989; Avery et al. 1990; Hayashi et al. 1991; Lee et al. 2002). This outflow consists of a pair of bipolar lobes aligned along the east-west (EW) direction (position angle P.A. $\approx$ 100°) and another pair of bipolar lobes aligned roughly in the north-south (NS) direction (P.A. $\approx$ 32°), with IRAS 19156+1906 located at their common center (Avery et al. 1990; Lee et al. 2002). The EW pair of lobes, and in particular the blueshifted, eastern lobe, is associated with several Herbig-Haro (HH) objects (Palacios & Eiroa 1999; López et al. 2006). Very Large Array (VLA) observations at 3.6 cm reveal two sources, VLA 1 and VLA 2, toward the center of the outflow (Anglada et al. 1991), although VLA 1 is likely a background source (Anglada et al. 1996; Girart et al. 1997). VLA 2 shows the characteristics of a thermal radio jet (jetlike morphology and partially optically thick free–free emission), and was first identified as the powering source of the EW pair of molecular lobes (Anglada et al. 1996). Recent, very sensitive, subarcsecond angular resolution (0″2–0″7) VLA observations at 3.6 cm and 7 mm resolve VLA 2 into several components. The two brightest sources at 3.6 cm, VLA 2A and 2B, are separated by 0″3 (90 AU in projection) and are possibly tracing embedded protostars (Anglada 2004; Carrasco–González et al. 2008). VLA 2A is associated with extended emission along a P.A. $\approx$ 115°. Two additional sources, believed to also trace embedded protostars, are identified at 7 mm: VLA 2C, located at the position of the water maser emission (Girart et al. 1997; Furuya et al. 2003), and VLA 2D, located $\approx$ 3° southeast of VLA 2A. Carrasco–González et al. (2008) suggest that the CO high-velocity emission and the HH objects are tracing three different outflows. One of them is the NS outflow possibly powered by VLA 2B. The other two are what previously was considered as the EW pair of lobes; one of the outflows has a P.A. $\approx$ 115° and is powered by VLA 2A, whereas the other one seems to be a “fossil” outflow with a P.A. $\approx$ 90°.

High angular resolution (3″5) VLA observations of L723 carried out by Girart et al. (1997) show that the NH$_3$ emission arises from a V-shaped structure that traces the dense molecular envelope around the embedded protostars. This structure is elongated roughly EW and is 0.15 pc long, with a mass of 7 M$_{\odot}$. The ammonia maps show evidence of heating and line broadening toward VLA 2. A second spot of heating is observed 10″ west of VLA 2. This western hot spot (WHs hereafter) is interpreted by Girart et al. (1997) as a very young protostar with an age shorter than 2 × 10$^4$ yr. The NH$_3$ structure is only partially traced by CS and N$_2$H$^+$ (Hirano et al. 1998; Chen et al. 2007). The dense envelope of L723 was also observed at submillimeter wavelengths (850 μm and 450 μm) by Shirley et al. (2002)
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and Estalella et al. (2003) using the continuum Submillimetre Common-User Bolometer Array (SCUBA) camera of the James Clerk Maxwell Telescope (JCMT). A strong millimeter source was found, peaking at the position of VLA 2, with a large extension that matches the high-density gas traced by NH₃.

In this paper, we present a study of the molecular and dust emission at scales of ∼ 1000 AU around the low-mass star-forming region of L723. In Section 2, we describe the observational procedure with the SMA. In Section 3, we describe the main results obtained with the SMA data. In Section 4, we present an analysis of the dust and H₂CO emission. In Section 5, we discuss the possible evolutionary scenarios of the sources in the region.

2. SMA OBSERVATIONS

The observations were carried out with the eight-antenna SMA⁴ array at Mauna Kea at 1.3 millimeters in 2004 August (compact configuration). The phase center was set at α(J2000) = 19h17m53.400 and δ(J2000) = 19°12′59.40. The phase calibrator used was QSO 1925 + 211, and QSO 1749 + 096 was used as a reference calibrator. Absolute flux and bandpass calibration was done by observing Uranus and Jupiter, respectively. The SMA correlator has a bandwidth of 2 GHz with 24 partially overlapping windows (chunks) of 104 MHz. All the chunks had 128 channels, except the second chunk which was configured to have 512 channels. The correlator was set up to observe the H₂CO 3–0, 3–2 line in the second chunk of the lower side band. Maps were made with the (u, v) data weighted by the associated system temperatures and using a robust weighting of 0.0 (continuum data), 0.5 (H₂CO) and 1 (other line data). Table 1 lists the basic information about the resulting maps, including the frequency of the lines or continuum, the channel resolution (for line observations), the resulting synthesized beam, and the rms noise of the maps.

3. RESULTS

3.1. Dust Continuum

The 1.35 mm continuum map shows that the emission is clearly resolved into two components, L723 SMA 1 and SMA 2, with similar intensities (see Figure 1) and separated by 2′9 (880 AU in projected distance) with a P.A. of 106°. These two components were previously detected by Launhardt (2004) at 3 mm. The strongest component, SMA 2, is associated with

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The table below lists the parameters of the SMA Observations:

| Observation | ν (GHz) | HPBW (arcsec) | P.A. (deg) | Δν (MHz) | Resolution (km s⁻¹) | Noise (mJy beam⁻¹) |
|-------------|--------|---------------|------------|----------|----------------------|-------------------|
| Continuum   | 222.31 | 3.3 × 1.5     | 79         | 4000     | 1.8                 |
| H₂CO 3–0, 3–2 | 218.222 | 3.1 × 1.8     | 76         | 104      | 0.28                | 175               |
| H₂CO 3–2    | 217.2385 | 3.2 × 2.1    | 76         | 104      | 1.07                | 78                |
| SiO 5–4     | 217.1050 | 3.2 × 2.1    | 76         | 104      | 1.12                | 60                |
| CN 2–1/5–2/3 | 226.8748 | 3.1 × 2.0    | 76         | 104      | 1.07                | 65                |
| CN 2–1/3–2/1 | 226.6595 | 3.1 × 2.0    | 76         | 104      | 1.07                | 88                |

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Footnote: ⁴ 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.
and see if the WHS could be detected, which yielded negative results.

The mass of the circumstellar material traced by the dust emission at mm wavelength, where it is optically thin is

\[ M = \frac{g S_b D^2}{\kappa_B B_v (T_{\text{dust}})} \]

with \( g \) being the gas-to-dust ratio, \( D \) the distance, \( S_b \) the flux density, \( \kappa_B \) the interstellar dust opacity coefficient and \( B_v \) the Planck function for a blackbody of dust temperature \( T_{\text{dust}} \).

The major source of uncertainty in the mass derivation is the poor knowledge of the distance (300 ± 150 pc). To derive the mass, we adopted \( g = 100 \) (Draine 2004), a dust mass opacity of \( \kappa_{350 \text{GHz}} = 0.9 \text{ cm}^2 \text{ g}^{-1} \) (Ossenkopf & Henning 1994). To estimate the temperature of the dust, we used the VLA NH$_3$ (1,1) and (2,2) transitions (Lee et al. 2002). The H$_2$CO emission at mm wavelength, where it is optically thin is

\[ S_N \propto B_0 \tau \text{ (integration time)} \]

where \( B_0 \) is the brightness temperature at the source and \( \tau \) is the optical depth. The H$_2$CO emission is concentrated around the 2 mm line, and the dust emission peaks at or very close to the 2 mm line. The H$_2$CO emission is optically thin, whereas around SMA 1 the peak emission \( S_N \propto B_0 \tau \). Figure 4 shows that the spectra of H$_2$CO have larger line widths than those of NH$_3$ (note that the (1,1) and (2,2) transitions have hyperfine components, which broadens the line, specially for the (1,1)).

Table 2

| Source  | \( \alpha(J2000) \) | \( \delta(J2000) \) | \( I_v \) (mJy beam$^{-1}$) | \( S_v \) (mJy) | Deconvolved Size (arcsec) | P.A. (deg) |
|---------|---------------------|---------------------|-----------------------------|----------------|--------------------------|------------|
| SMA 1   | 19$^{h}$17$^m$53$^s$.884 | 19$^\circ$12$'$18.5 | 29.9 ± 1.8                  | 45 ± 4         | (2.0 ± 0.3) x (≤ 0.6)     | 56 ± 9     |
| SMA 2   | 19$^{h}$17$^m$53$^s$.694 | 19$^\circ$12$'$19.6 | 33.7 ± 1.8                  | 59 ± 4         | (2.3 ± 0.2) x (1.0 ± 0.2)  | 73 ± 6     |

Note. * Values corrected by the primary beam of the SMA antennas.

Table 3

| Source  | \( S_v(1.35 \text{ mm}) \) (mJy) | \( T_{\text{dust}} \) (K) | \( M \) (\( M_\odot \)) |
|---------|-------------------------------|--------------------------|--------------------------|
| All     | 128 ± 6                       | 25                       | 0.24                     |
| SMA 1   | 45 ± 4                        | 25                       | 0.09                     |
| SMA 2   | 59 ± 4                        | 25                       | 0.11                     |
| WHS     | ≤ 5.7                         | 25                       | ≤ 0.011                  |

Note. * To estimate the total mass we took into account the contribution of the mass from the 24 mJy excess of emission of the natural map (obtained adopting a temperature of 20 K).

Since VLA 2 is a thermal radio jet with a well defined orientation (Anglada et al. 1996), position–velocity (PV) plots along (\( P.A. = 116^\circ \)) and perpendicular (\( P.A. = 26^\circ \)) to the radio-jet orientation were made crossing VLA 2, which lies at the peak of SMA 2 (Figure 5). The PV plot along the radio-jet direction passes very close to SMA 1 (see Figure 5). In the direction perpendicular to the jet, the H$_2$CO shows a velocity gradient (\( ∼ 0.8 \text{ km s}^{-1} \) within 1" around VLA 2) that could be indicative of rotation. In the direction along the radio jet, there is an overlap of the emission between SMA 2 and SMA 1. Nevertheless, at the position of SMA 1, the H$_2$CO emission shows a relative minimum. In Figure 5, we also show the PV plot centered on SMA 1 with a position angle of P.A. = 30°, nearly perpendicular to the PV along the VLA 2 radio-jet direction. This PV plot shows two weak peaks at different velocities, \( v_{\text{LSR}} \simeq 10.8 \) and 11.9 km s$^{-1}$, which are slightly shifted in position (\( ∼ 0.9^\prime \)).

As in the case of the continuum emission, no emission is detected at the position of the ammonia WHS (see Figure 4). The 3σ upper limit from the SMA map is 0.53 Jy beam$^{-1}$ (2.4 K).

3.3. SiO

The SiO 5–4 line is marginally detected toward the SMA 1 and SMA 2 system (see Figure 6). The emission appears clumpy and elongated in the NW–SE direction (\( P.A. = 145^\circ \)), with the strongest emission about 11'' SE of SMA 1. Taking into account the fact that the SiO is a tracer of molecular shocks, the emission appears relatively “quiescent”: it is only slightly redshifted with respect to the systemic velocity (the emission is detected in the \( v_{\text{LSR}} = 11.31 \) and 12.44 km s$^{-1}$ channels) and the line width, \( \Delta v \simeq 2 \text{ km s}^{-1} \), is only slightly larger than that of the lines tracing the dense circumstellar material such as H$_2$CO and ammonia.

The emission is apparently more associated with SMA 1, but given the complex outflow activity in the region (Lee et al. 2002; Carrasco–González et al. 2008) it is difficult to elucidate with which outflow and powering source it is associated. Nevertheless, at the SiO velocity and location there is strong CO emission (see channel maps from Lee et al. 2002), which
suggested that the SiO is tracing a region of interaction between the dense envelope and the outflow (Codella et al. 1999).

### 3.4. Other Molecules

Several hyperfine transitions of the CN 2–1 rotational transition were detected (Figure 7). The strongest line is a blend of three hyperfine lines, the $F = 7/2–5/2, 5/2–3/2$ and $3/2–1/2$ of the $J = 5/2–3/2$ set. The $J = 3/2–5/2, F = 1/2–3/2$ hyperfine line is also marginally detected. Although there are other hyperfine transitions within the bandwidth their relative intensities were too small to be detected (see Figure 7). The integrated intensity of the detected transitions (Figure 8) shows that the emission is concentrated around VLA 2, being only weakly detected toward SMA 1. We also marginally detected the DCN 3–2 line toward the two sources (Figures 8 and 7).

Despite the poor spectral resolution ($\sim 1 \text{ km s}^{-1}$), these two molecules show emission at the ambient molecular gas velocity with narrow line widths ($\sim 1 \text{ km s}^{-1}$).

### 4. ANALYSIS

#### 4.1. Model of the Dust Emission

The dust emission from SMA 1 and SMA 2 is partially resolved with sizes of several hundred AU, which suggest that a significant contribution to the emission is possibly coming from the infalling envelopes around the disks. Figure 9 shows clearly that the correlated amplitude in the visibility data centered on VLA 2 comes mostly from an extended component, although there is also a weaker unresolved component with a flux density of $\sim 20 \text{ mJy}$ that appears to be dominant at visibility radii larger than $\sim 40 \lambda$. To better characterize this apparently
compact component, additional maps were obtained using only visibilities that have a radius in the \((u, v)\)-plane larger than 45 \(k\lambda\). The resulting map of the emission from SMA 1 and SMA 2 appears to be compact. Both sources are unresolved with fluxes of 19.7 ± 2.4 and 13.3 ± 2.4 mJy for SMA 2 and SMA 1, respectively. This is about one third of the total flux density detected by the SMA for each source. A Gaussian fit to SMA 2 using the task IMFIT of AIPS yields an upper limit of the diameter of \(\sim 1''\). The other source, SMA 1, is too weak to do the same fitting. In any case, the compact dusty components seem to arise from a structure with a radius of \(\lesssim 180\) AU.

Without proper modeling, it is not possible to elucidate whether this compact component traces the disk or the inner part of the envelope. Interestingly, the peaks of the two components are slightly shifted (\(\sim 0''\)) with respect to the peak position given in Table 2. This could be produced by a somewhat asymmetrical distribution of the gas and dust in the envelope, which will not be a surprise because of the multiplicity detected with the VLA at the center of SMA 2. The compact component of SMA 2 coincides well with the centimeter source VLA 2A detected by Carrasco–González et al. (2008; the position of the dust is \(\alpha(\text{J2000}) = 19^{h}17^{m}53^{s}.666\) and \(\delta(\text{J2000}) = 19^{\circ}12^{'}19.63\)\). The peak of the SMA 1 compact component (\(\alpha(\text{J2000}) = 19^{h}17^{m}53^{s}.920\) and \(\delta(\text{J2000}) = 19^{\circ}12^{'}18.52\)\) is displaced to the northwest with respect to VLA 2D by 0''0.67 (see Figure 10). Given the weak detection of this source at both 1.35 and 7 mm (5\(\sigma\) and 4\(\sigma\) respectively) further more sensitive observations are needed to confirm this displacement.

In order to characterize the properties of the double cores, we modeled the dust emission assuming, for simplicity, that it arises from two independent optically thin twin circumstellar envelopes with a radial density and temperature profiles at the position of the dusty sources detected with the SMA. The model integrates the dust emission assuming spherical symmetry from an inner radius, \(R_{\text{inner}}\) to an outer radius of 1.5 × 10^4 AU (this value is somewhat arbitrary and does not affect the fit because the emission at these scales is filtered out by the SMA). We do not include the possible contribution from the circumstellar disks, since it is possible that at this stage the disks are small, with a radius of \(\lesssim 30\) AU (Rodríguez et al. 2005). The three possible protostars associated with SMA 2 are separated by a projected distance of \(\sim 0.9\) or 270 AU (Carrasco–González et al. 2008) below the angular resolution of our observations. If these sources are truly nearby protostars, it is possible that there is a cavity in the envelope between these sources. To check whether there is a significant cavity, we used different radii of 30, 100, and 180 AU. We adopted the density profile expected for an infalling envelope, \(n(r) \propto r^{-1.5}\), up to an infall radius, \(R_{\text{infall}}\). Beyond \(R_{\text{infall}}\) we used a \(r^{-2}\) density profile. In order to minimize the free parameters in the model, we

Figure 3. Color image of the first-order (bottom panel) and second-order (top panel) moments of the \(\text{H}_2\text{CO}\) emission toward L723 VLA 2 superposed with the zero-order moment (integrated emission) contour map. The color image level is shown in the right side of the panels. The first contour is 0.1 Jy beam\(^{-1}\) km s\(^{-1}\), and the contour levels are 0.3 Jy beam\(^{-1}\) km s\(^{-1}\). The crosses show the position of the dust sources SMA 1 and SMA 2. The synthesized beam of the maps is shown in the bottom right corner of the bottom panel.

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

Figure 4. Spectra of the \(\text{H}_2\text{CO}\) 30,3–20,3, \(\text{NH}_3\) (2,2) and (1,1) toward the position of SMA 2 (left panels), SMA 1 (central panels) and WHS (right panels). The spectra were taken from channel maps at similar angular resolution, \(\sim 3''\). The \(\text{NH}_3\) spectra are taken from Girart et al. (1997).
adopted a $R_{\text{infall}} = 1000$ AU, the value found by Shirley et al. (2002). For a dusty cloud heated by an internal source, the temperature radial profile can be characterized as $T \propto r^{-3/4+\beta}$ (Kenyon et al. 1993), where $\beta$ is the dust emissivity spectral index. The value used is $\beta = 1.5$, which was derived from 850 and 450 $\mu$m SCUBA observations (Estalella et al. 2003). We adopted a 1.35 mm dust opacity of $\kappa \approx 0.9$ cm$^2$ g$^{-1}$, which should be adequate for dusty particles with ice mantles at densities of about $10^6$ cm$^{-3}$ according to Ossenkopf & Henning (1994). Additional free parameters were the density $n_0$ and temperature $T_0$ at a radius of 1000 AU. Intensity profiles were obtained for each set of $R_{\text{inner}}$, $n_0$, and $T_0$ and converted to a two-dimensional image map. These modeled maps were multiplied by the primary beam response of the SMA antennae, assumed to be 56$^\prime$ at 1.35 mm. Two sets of visibility data were generated: one obtained by subtracting the modeled map to the visibility continuum data of the SMA observations. The other set was obtained by replacing the values of observed visibilities with the values expected from the modeled map. Maps of the residual and of the model were obtained from the visibilities using the same parameters as the SMA maps shown here. The rms and bias were finally computed for these residual maps. The bias is defined as the absolute flux density of the residual on a given region (the region where the emission is detected). The models with an inner radius of 180 AU cannot reproduce well the SMA data, which suggests that if there is an inner cavity (produced by the presence of a multiple protostellar system), it is not big enough to affect the simple model used here. With respect to the solutions with an inner radius of 30 and 100 AU, there is, for both, a family of possible solutions in the $T_0$–$n_0$ plane. The plot of the rms for these two inner radii in the range of densities and temperatures computed is shown in Figure 11. The best set of solutions can be expressed as $n_0 = 1.5 \times 10^5 [T_0/30$ K]$^{-1.2}$ cm$^{-3}$ and $1.1 \times 10^6 [T_0/30$ K]$^{-1.5}$ cm$^{-3}$ for the 30 and 100 AU inner radii, respectively.

The VLA ammonia maps from Girart et al. (1997) can be used to further constrain the model. At the positions of SMA 1 and SMA 2, the kinetic temperature estimated from the NH$_3$ (1,1) and (2,2) maps is $\approx 25$ K (see Section 3.1). Since the beam of the VLA maps is $\approx 8.5$", it is reasonable to adopt the value of 1.75 or 520 AU, as the radius at which the gas is at 25 K. This implies that the temperature profile of the dust can be written as $T = 20 \times (r/1000$ AU)$^{-0.35}$ K. The previous two equations that give the best set of solutions yield a density profile of $n$(H$_2$) $= 2.4 \times 10^6 (r/1000$ AU)$^{-1.5}$ cm$^{-3}$ for $R_{\text{inner}} = 30$ AU, and of $1.8 \times 10^6 (r/1000$ AU)$^{-1.5}$ cm$^{-3}$ for $R_{\text{inner}} = 100$ AU. Figure 9 shows that the correlated flux in the visibility domain for the model with $R_{\text{inner}} = 30$ AU, $T_0 = 20$ K, and $n_0 = 2.4 \times 10^6$ cm$^{-3}$ fits reasonably well the SMA data. The synthetic maps from the model and the residuals for this particular solution also show the remarkable similitude with the L723 dusty binary system (see Figure 12). Indeed, from the residual map obtained using only the longest baselines (see right panels of Figure 12) the model of the binary envelope can
Figure 7. Spectra of the H$_2$CO 3$_0$–2$_0$, DCN 3–2, CN N = 2–1, J = 5/2–3/2, and J = 3/2–1/2 obtained averaging a region of 7″ × 5″ around SMA 1 and SMA 2. The CN and DCN spectra has a lower velocity resolution (∼1.0 km s$^{-1}$). For the CN hyperfine transitions, a vertical dashed line indicates the position of the expected hyperfine transition with the height proportional to its relative intensity.

account within the rms level of the map the compact, apparently unresolved, component of the two dusty sources, without the need of invoking the presence of an accretion disk (see the discussion section). On the other hand, the residual map done using all the visibilities shows some significant residuals (at a ∼ 4σ level): there are some positive residuals northeast of SMA 2 and extended negatives on the southern side of the dust emission from both SMA 1 and SMA 2. These residuals could be due to the departure from the spherical symmetry of the data.

We can also compare the density we found with the value derived by Dartois et al. (2005) by modeling the spectral energy distribution of L723. They estimated that at 100 AU the density is $2.2 \times 10^7$ cm$^{-3}$, which is a factor of 2.6–3.4 lower than what we derive for $T_0 = 20$ K. This difference could be due to the different dust opacity and the different density profile used.

The derived density distribution can be used to estimate the mass of the two envelopes. The equivalent radius of the SMA shortest baselines in the visibility domain (∼12 kλ) is 3′′75 (1125 AU). The combined mass for the two envelopes within a radius of 1125 AU is in the 0.14–0.36 $M_\odot$ range for a
Figure 9. SMA-correlated flux for the 1.35 mm continuum emission vs. UV distance (in units of kλ) at the position of SMA 2. The correlated flux was derived by vector averaging the amplitude of the visibilities over annular bins. The bins have a width of 3.3 kλ for radius lower than 50 kλ and of 10 kλ for larger radii. The solid line shows the expected value for the amplitude assuming no signal (i.e., the “zero bias”). The dotted line shows the expected flux for an unresolved source of 20 mJy. The open squares show the expected correlated for the model $T_0 = 20$ K and $n_0$(H2) = 2.4 $\times$ 10$^6$ cm$^{-3}$ described in Section 4.1.

As an additional test for the model, we have used a 3.2 mm continuum map obtained with the Berkeley–Illinois–Maryland Association (BIMA) array. These observations were carried out in 2003 September in the C configuration. The continuum was observed simultaneously with the N2H+ 1–0 and CH3OH 20–10 A and 2$_{-1}$–1$_{-1}$ E lines (J. M. Masqué et al. 2009, in preparation). The dust model was extrapolated to this wavelength, and the standard position of the BIMA antennas at the C configuration was used to create a synthetic BIMA map using the same procedure as the one described for the SMA. The synthetic maps were obtained for the $R_{\text{inner}} = 30$ AU, $T_0 = 20$ K, and $n_0 = 2.4 \times 10^6$ cm$^{-3}$ model. Figure 13 shows that the model also reproduces reasonably well the BIMA map.

4.2. Modeling the H2CO Emission

Once the dust emission was successfully modeled, we modeled the H2CO emission using the one-dimensional version of Ratran (Hogerheijde & van der Tak 2000). This is a Monte Carlo code that calculates the radiative transfer and excitation of molecular lines. The code is formulated from the viewpoint of cells rather than photons, which allows the separation of local and external contributions of the radiation field. This gives an accurate and fast performance even for high opacities (Hogerheijde & van der Tak 2000). The H2CO collisional rates used were derived by Green (1991) and were downloaded from the Leiden Atomic and Molecular Database (Schöier et al. 2005).

We modeled the emission as arising from two cores with the same density and temperature profile, as suggested by the dust modeling. Since there is a family of possible solutions, we fixed the temperature and density profiles derived in the previous section that agrees with the ammonia rotational temperature: $T = 20 (r/1000\ AU)^{-0.35}$ K and $n$(H2) = 2.4 $\times$ 10$^6 (r/1000\ AU)^{-1.5}$ cm$^{-3}$ (the solution for $R_{\text{infall}} = 30$ AU).

The kinematics is not well resolved with our observations, so we assume that the gas is in free-fall collapse. This is marginally suggested by the line profile at the position of SMA 1 and SMA 2 (see Figure 14 and Section 5.1). We adopted a velocity field for the free-falling gas of $v_{\text{infall}} = 0.5 (r/1000\ AU)^{-0.5}$ km s$^{-1}$ and an intrinsic linewidth of 0.6 km s$^{-1}$. Using these values, the modeled line width was similar to the H2CO values measured with the SMA and, in any case, the use of these values should not critically affect the derivation of the H2CO properties (Jørgensen et al. 2004).
Figure 11. Plots show the locus of best solutions represented by the function of the rms of the residual map derived by subtracting the dust model for an inner radius of 30 AU (left panel) and 100 AU (right panel) to the SMA visibility data of the 1.3 mm continuum emission. Levels are in steps of 3 times the rms of the original SMA map, 1.5 mJy beam$^{-1}$. The dashed gray line shows the line of approximately set of best solutions represented as the function $n(H_2) = 1.5 \times 10^6 [T/30 K]^{-1/2} \text{ cm}^{-3}$ (left panel) and $n(H_2) = 1.1 \times 10^6 [T/30 K]^{-1/2} \text{ cm}^{-3}$ (right panel).

To run RATRAN we adopted a fixed H$_2$CO abundance within a shell with an inner and an outer radii, $R_{in}$ and $R_{out}$, respectively, with the abundance being zero outside the shell. We ran a series of models with RATRAN using a range of values for $R_{in}$ and $R_{out}$ and for the p–H$_2$CO abundance, $X_{[p-H_2CO]}$. Since the H$_2$CO emission is significantly different between the two envelopes, we made synthesized maps using different sets of ($R_{in}$, $R_{out}$, $X_{[p-H_2CO]}$) values for SMA 1 and SMA 2. Synthesized maps with 16 channels and with a spectral resolution of 0.28 km s$^{-1}$ were generated. We took into account that the systemic velocity of the H$_2$CO between the two cores differs by $\approx 0.2$ km s$^{-1}$ (see Table 4). The maps were multiplied by the primary beam of the SMA and then converted to visibilities. Maps of the model and of the residuals (generated by subtracting the model to the data in the visibility domain) were made in the same fashion as for the SMA dust emission maps (see Section 4.1).

We explored values within the range of $8 \times 10^{-11}$–$1 \times 10^{-8}$ for $X_{[p-H_2CO]}$, 30–240 AU for $R_{in}$, and 300–$10^4$ AU for $R_{out}$. In order to find the best set of solutions, we computed separately the $\chi^2$ parameter for the spectra at the SMA 1 and SMA 2 positions and for the total flux density within a region of $11'' \times 8''$ centered around the twin envelopes. Table 5 shows the range of the best fits found. The range of parameters is better constrained for SMA 2 than for SMA 1. This is due to its higher intensity and its apparently more compact size. Indeed, the model yields solutions that imply that the H$_2$CO around SMA 2 should arise from the inner region of the envelope. More specifically, the outer radius cannot be significantly larger than 600 AU, but not lower than 300 AU (otherwise the emission would be unresolved, which is not the case). The SMA 2 abundance is also

![Figure 12. SMA synthetics maps for the dust model $R_{min} = 30$ AU, $I_0 = 20$ K, and $n_0 = 2.4 \times 10^6 \text{ cm}^{-3}$ described in Section 4.1. Left: the model (top) and residual (bottom) dust maps obtained using all the visibilities observed with the SMA and using robust of 1. Contours levels for the model map are $-3, 3, 5, 7$, and $21$ times $1.5$ mJy beam$^{-1}$, the rms of the map. Contour levels for the residual map are $-3, -2, 2, 3$, and $4$ times $1.5$ mJy beam$^{-1}$. Right: the model (top) and residual (bottom) dust maps obtained using visibilities with a radius larger than $45$ k$\lambda$ and natural weighting (as in Figure 10). Contour levels are $-3, -2, 2, 3, 4, 5, 6$, and $7$ times $2.4$ mJy beam$^{-1}$. The synthesized beams are shown in the lower left corner of each panel. The crosses show the position of SMA 1 and SMA 2.](image-url)
Figure 13. Left: BIMA map of the 3.2 mm continuum emission obtained with the C configuration in 2003 September. The synthesized beam, 10′′6 × 6′′7 and P.A. = −7°, is shown in the bottom right corner. Contours are −2, 2, 3, 4, 5, 6, and 7 times 2.8 mJy beam$^{-1}$, the rms noise of the map. The crosses show the position of SMA 1 and SMA 2. Middle: BIMA synthetic map at 3.2 mm continuum at the C configuration for the dust model $T_0 = 20$ K and $n$(H$_2$)$_0 = 2.4 \times 10^6$ cm$^{-3}$ described in Section 4.1. Contours are the same as in the previous panel. Right: BIMA residual map obtained from the previous two maps.

relatively well constrained, $X[p$–H$_2$CO$] \simeq (3–10) \times 10^{-10}$. For SMA 1, the best set of solution yields H$_2$CO abundances in the range of $X[p$–H$_2$CO$] \simeq (8–30) \times 10^{-11}$, but with values always lower than for SMA 2: the best solutions are found when SMA 2 abundances are a factor of 3 to 10 higher than for SMA 1. Another difference with respect to SMA 2 is that the best models for SMA 1 have a larger outer radius than for SMA 2, $R_{out} \simeq 600–5000$ AU.

Figure 15 shows the synthesized model, the SMA data and the residual for one of the best solutions found (see the figure caption for details). Figure 14 shows the spectra toward SMA 1 and SMA 2 for the same model and for the SMA data. These figures show that the models fit the observations reasonably well, although the residuals appear up to about a 4σ level. In spite of the good match between the synthesized and observed spectra for the two sources, the model reproduces better morphology of SMA 2 than that of SMA 1. The morphology mismatch between SMA 1 and the synthesized map occurs for all the models. This suggests that the emission, specially from SMA 1, departs from the idealized spherical model used with the assumption that the H$_2$CO arises only within a shell. Indeed, the position–velocity cuts in two orthogonal directions centered on SMA 1 (see Figure 5) show a double peak in one of them and what roughly appears to partially a “donut,” centered on SMA 1, in the other cut (partially because of the overlap with SMA 2 in the NW side). This suggests that the H$_2$CO emission may not come from the shell of a spherical envelope but from a contracting and somewhat flattened shell or torus. For example, such a case was more clearly observed in the CS emission associated with the dense core ahead of HH 80N (Girart et al. 2001). The marginal evidence that the H$_2$CO arises from a torus supports the idea that the emission does not come from a spherical configuration. However, despite the limitations of the adopted approach, given the limited signal-to-noise ratio obtained and the use of only one transition, the results from the modeling should be regarded as a good first approximation to the properties of H$_2$CO in these two cores.

The derived p–H$_2$CO abundances are compatible with the value found by Jørgensen et al. (2005), $9.6 \times 10^{-10}$, from single-dish observations, and are also within the range of values found for the so-called outer part of the circumstellar envelopes associated with Class 0 sources (Jørgensen et al. 2005; Maret et al. 2004), which are defined as the region where temperatures are lower than $\simeq 100$ K. In the inner region of the envelopes, where the temperature is $\gtrsim 100$ K, the icy grain mantles evaporates and molecular abundances are expected to increase significantly: the H$_2$CO reaches abundances between $10^{-8}$ and $10^{-6}$ (Jørgensen et al. 2005; Maret et al. 2004). Our model did not take into account this warm component. Nevertheless, the reasonable solutions found in this paper imply that the total amount of H$_2$CO in the inner warm region is not significant, despite the very high H$_2$CO abundance expected. This can be explained by the fact that for L723, the warm region is very small due to its low total bolometric luminosity, $3.4 L_\odot$ (the temperature of 100 K is reached at a radius of 10 AU).

5. DISCUSSION

5.1. The Twin Cores

The dust emission reveals two similar substructures, with SMA 2 being only slightly more massive than SMA 1 (Table 2). In fact, the modeling of the emission suggests that within the observational uncertainties (sensitivity and angular resolution) the dust properties of the two cores can be accounted as arising from “identical” twin cores. However, these twin cores have different molecular properties. The CN 2–1 and H$_2$CO 3$_{03}$–2$_{02}$
at the position of the two cores (Figure 14) is an additional marginal evidence of infall motions.

Previous observations find clear star formation signatures associated with the SMA 2 core. First the presence of a well studied thermal radio jet, VLA 2A, pinpoint the position of a protostar that is powering the EW molecular outflow (Anglada et al. 1996; Carrasco–González et al. 2008). VLA high angular resolution observations reveal the presence of a water maser, and 7 mm and 3.6 cm sources (VLA 2B and 2C) ~ 0.5 around VLA 2A (Girart et al. 1997; Carrasco–González et al. 2008). Carrasco–González et al. (2008) interpret these as a young stellar system, which is forming the 150 AU vicinity (in projected distance) around VLA 2A. In addition, they find that VLA 2B may be powering the NS molecular outflow. This stellar system is being formed inside the SMA 2 core. In contrast, there are not known signs of outflow activity toward SMA 1, yet. There is only marginal dust emission detected at 7 mm, labeled as VLA 2D (Carrasco–González et al. 2008).

In conclusion, our study and analysis of SMA 1 and SMA 2 show that they have almost identical properties (mass, and density and temperature distribution) and that there is marginal evidence of infall motions in both. However, the H₂CO abundance toward SMA 2 is significantly higher than in SMA 1. Since SMA 2 shows clear outflow activity, in contrast with SMA 1, this suggests that SMA 2 is more evolved (due to a higher infall rate or because it is older). In any case, they are not “identical” twin cores but “fraternal” twin cores.

### 5.2. The Mass Reservoir Around the Class 0 Protostellar System

The total mass derived from the SMA observations is less than 10% of the whole dense core, derived from SCUBA JCMT observations at 850 and 450 μm (Estalella et al. 2003) or from VLA NH₃ observations (Girart et al. 1997). That is, the mass accreting to the protostars (or to the disks) at scales of ≲ 1000 AU is only a small part of the dense core. In addition, from the modeling, we found that the dust emission detected by the SMA at 1.35 mm seems to arise from the dense twin envelopes, SMA 1 and SMA 2, and within the limits of our sensitivity there is no need to invoke to the presence of protostellar disks. This means that the contribution from the disks at 1.35 mm should not be higher than ≲ 8 mJy (the 5σ value of the continuum residual map of Figure 12). Assuming that the disk has a temperature of 50 K, the upper limit of the disk mass is 6 × 10⁻²²M⊙. This mass would be higher if the dust emission from the disk is not optically thin, but it would be lower if the temperature is higher. In any case, this suggests that the disk mass is less than 10% of the mass of each of the twin cores. Thus, the large-scale (0.1 pc) molecular envelope traced by NH₃ or SCUBA contains most of the mass or, in other words, it is still the major reservoir of mass to keep the star formation going on. Therefore, L723 seems to be in a very early phase of star formation.

It is clear that fragmentation is occurring at different levels. The 0.1 pc scale molecular envelope has fragmented at the center and at scales of ≈ 1000 AU into two cores, SMA 1 and SMA 2. At the same time, at least one of these cores,

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**Figure 15.** Channel maps of one of the best models, the SMA data and the residual (SMA–model) for the H₂CO 3_03–2_02 emission. Contours are −3, −2, 2, 3, 4, 5, 6, 7, and 8 times 0.17 mJy beam⁻¹. The synthesized beam is shown in the lower right corner of the lower right panel. The crosses show the position of the dust sources SMA 1 and SMA 2. The parameters for this model are X(p–H₂CO) = 3 × 10⁻⁸, Rₙ = 240 AU, and R₉₅ = 600 AU for SMA 2, and X(p–H₂CO) = 1 × 10⁻⁹, Rₖ = 60 AU, and R₉₅ = 5000 AU for SMA 1. The V₁₂₃₄ velocity of the channels is shown in the lower left corner of the right panels.
SMA 2, has undergone additional fragmentation at scales of \( \lesssim 150\text{AU} \), forming a multiple stellar system. However, we note that within the uncertainties, the SMA 2 can be modeled as a single envelope down to a radius of 30 AU. It is interesting to note that whatever is the fragmentation process, which is acting in the different scales (turbulence, the initial magnetic field and angular momentum configuration), is occurring within a 0.1 pc dense envelope that appears to be very quiescent at scales of few thousands AU outside its center according to the NH\(_3\) data (Girart et al. 1997): line widths of only \( \lesssim 0.5\text{ km s}^{-1} \) and small velocity gradients, of 3 km s\(^{-1}\) pc\(^{-1}\).

6. SUMMARY

We present continuum and line 1.35 mm high angular resolution observations (\( \simeq 3'\)) carried out with the SMA toward the low-mass protostellar region in the L723 dark cloud. We detected emission of the dust, the H\(_2\)CO 30–30, DCN 3–2, and SiO 5–4 transitions, as well as a few lines of the CN J21 transition. We performed a radiative transfer analysis of the dust emission as well as for the H\(_2\)CO line in order to constrain the physical and chemical conditions of the two cores. The main results of the paper can be summarized as follows.

1. The dust emission arises from two similar cores, SMA 1 and SMA 2, separated by 2'9 (880 AU in projected distance) and with masses of 0.06 and 0.08 \( M_\odot \), respectively. They are partially resolved, with deconvolved sizes of \( \simeq 500\text{ AU} \). SMA 2 is associated with VLA 2 and water maser emission. We modeled the dust emission from the two cores assuming that the cores have a density and temperature radial distribution of the type \( n(r) \propto r^{−1.5} \) and \( T \propto r^{−0.35} \). We found that within the uncertainty achieved, the two cores can be considered almost “identical” twins. The best set of solutions are those with a density and temperature that match the following expression: \( n_0(\text{H}_2) \simeq 1.1 \times 10^6 [T_0/30\text{ K}]^{1.2} \text{ cm}^{-3} \) (\( n_0 \) and \( T_0 \) are the density and temperature at a radius of 1000 AU). The model shows that all the emission detected can arise from the cores, with possibly no evidence of contribution from the accretion disk, which yields an upper limit of the disk mass of \( \lesssim 6 \times 10^{-3}\text{ }M_\odot \).

2. The H\(_2\)CO emission is concentrated around the 2 mm continuum sources, SMA 1 and SMA 2, although the emission is brighter toward SMA 2. The kinematics of the two sources is difficult to disentangle because their separation is similar to the angular resolution. Nevertheless, there is marginal evidence of infall motions in both sources (double peak line with brighter blueshifted component), a velocity gradient around SMA 2 indicative of rotation and that the H\(_2\)CO in SMA 1 arises from a contracting and somewhat flattened structure. The linewidth of H\(_2\)CO has values in the 1.2–1.7 km s\(^{-1}\) range, which is \( \lesssim 50\% \) larger than the values measures for the NH\(_3\) lines by Girart et al. (1997). The H\(_2\)CO emission was modeled adopting the density and temperature profile constrained by the dust emission. We used RATRAN assuming a fixed p–H\(_2\)CO abundance within a shell with an inner and an outer radii \( R_\text{in} \) and \( R_\text{out} \), respectively, being the abundance zero outside the shell. Reasonable models were found for a p–H\(_2\)CO abundance range of \((3–10) \times 10^{-10}\) and \((8–30) \times 10^{-11}\) for SMA 2 and SMA 1, respectively, but with the SMA 1 abundance lower than the SMA 2 by a factor of 3–10. The best models are those that have a more compact emission in SMA 2 (\( R_\text{out} \simeq 300–600\text{ AU} \)) than in SMA 1 (\( R_\text{out} \simeq 600–5000\text{ AU} \)). The p–H\(_2\)CO abundances found are compatible with the value of the outer part of the circumstellar envelopes associated with Class 0 sources. The total amount of H\(_2\)CO in the inner warm region of the circumstellar envelopes (where \( T \gtrsim 100\text{ K} \)) is not significant, despite the very high H\(_2\)CO abundance expected (e.g. Maret et al. 2004). This can be explained by the fact that for L723, the warm region is very small (a radius of \( \lesssim 10\text{ AU} \)) due to its low total bolometric luminosity, 3.4 \( L_\odot \).

3. The DCN and CN lines arise from the same region as the dust and H\(_2\)CO. The CN emission peaks clearly toward SMA 2, whereas the DCN shows similar emission in SMA 1 and SMA 2.

4. SiO is detected marginally at slightly redshifted velocities around SMA 1 and SMA 2, and is possibly tracing a region of interaction between the dense envelope and the outflow.

5. The WHS, detected by Girart et al. (1997) from NH\(_3\) observations as a spot of local heating, is not detected by the SMA (line and continuum) observations. The nondetection of the 1.35 mm emission yields an upper limit of the WHS mass of \( \lesssim 0.01\text{ }M_\odot \).

6. The above results suggest that although SMA 1 and SMA 2 cores have almost identical physical properties (density and temperature distribution), they are rather “fraternal” twins, with SMA 2 being in a more evolved stage. Thus, SMA 2 is harboring an active multiple low-mass protostellar system (VLA 2A, 2B and 2C), powering at least one molecular outflow (Carrasco–González et al. 2008). In contrast, there are no signs of outflow activity toward SMA 1.

7. The large-scale (0.1 pc) molecular envelope (traced by NH\(_3\) or SCUBA) is the major reservoir of mass to keep the star formation going on (it contains about \( \gtrsim 90\% \) of the mass), which suggests that L723 is still in a very early phase of star formation.

8. Fragmentation is occurring at different levels at the center of the L723 dense molecular cloud: at scales of \( \gtrsim 1000\text{ AU} \), the cloud has fragmented into two cores: SMA 1 and SMA 2. SMA 2 has undergone additional fragmentation at scales of \( \gtrsim 150\text{AU} \), forming a multiple stellar system (Carrasco–González et al. 2008). Whatever is the fragmentation process that is acting at the different scales (turbulence, the initial magnetic field and angular momentum configuration) it is occurring within a dense envelope that appears to be quiescent at scales of few thousands AU.

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